Power and Rate Optimization in Shared-Spectrum Wireless Communication Networks

Mirtavoosi Mahyari, Mohammad

Awarding institution:
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Author: Mohammad Mirtavoosi Mahyari

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Mohammad Mirtavoosi Mahyari

Institute of Telecommunications
Department of Electronic Engineering
King's College London

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"A pessimist sees the difficulty in every opportunity; an optimist sees the opportunity in every difficulty."

Winston Churchill

Acknowledgment

The first part of this acknowledgement is dedicated to my dear parents. My father, whose continuous support and encouragement has provided me with the confidence and motivation to continue my education to its fullest. Along with my mother, to whom I owe all my success due to the moral and intellectual education I received from her. I would also like to thank the rest of my family.

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Abstract

The growth of wireless applications and the emerging technologies require more efficient management of frequency spectrum. Adaptive resource allocation (i.e. transmission power and transmission rate) and opportunistic spectrum sharing are two key techniques with enormous potential to enhance the efficient utilization of the precious bandwidth and optimizing the performance. Adaptive algorithms are a vital feature of radio resource management (RRM) in third generation (3G) communication systems, and cognitive radio (CR) is a valuable technique with tremendous potential for improving the utilization of the radio spectrum. On the other hand, transition from the current 3G cellular communication systems to the fourth generation (4G) would happen gradually and take several years. During this period, both 3G and 4G technologies are expected to co-exist, and the aforementioned CR technology and adaptation techniques are suitable candidates to be used by service providers for achieving higher data rates in the future heterogeneous networks. In this thesis, novel adaptive transmission algorithms will be developed for shared-spectrum CR networks in the context of direct-sequence code division multiple access (DS-CDMA).

This thesis makes several contributions. First, adaptive transmission is integrated into spectrum sharing problem. The joint optimization of power and rate is investigated, where optimality is in the sense of maximizing the average spectral efficiency of the reference cognitive user (CU). A closed-form solution for the optimal outer loop power control target signal-to-noise ratio (SNR-target) of the reference CU is derived. The optimization is conducted when the reference CU is using interference-limited opportunistic spectrum access (IL-OSA) technique for utilizing the primary spectrum simultaneously with the primary users. The proposed optimization algorithm's performance is analyzed for a case, wherein the reference CU exploits the licensed spectrum subject to non-violation of the average and the peak received-interference constraints. Moreover, the evaluation is extended for more reliable scenario with better performance, wherein the imposed peak-interference constraint is dynamically set as a function of the number of active primary and cognitive users that exploit the licensed frequency band.

Second, a shared-spectrum CR system is considered and the reference CU's total average spectral efficiency is derived when it uses access-bounded opportunistic spectrum access (AB-OSA) for exploiting the primary spectrum. The gain that can be attained by using a CR technology is highlighted and the reference CU performance is investigated subject to average transmit power constraints.

Finally, a novel access technique is proposed to overcome the AB-OSA limitation in CDMA/CDMA, CR networks. This method is referred to as access-bounded-interference-limited opportunistic spectrum access (AB-IL-OSA). This novel access strategy incorporates a mixed access- and interference- limited spectrum access strategy through spectrum sensing, to maximize the achievable spectral efficiency of the CUs.

Various OSA strategies were proposed for CDMA-based CR networks to achieve a balance between the full exploitation of the primary spectrum and the inflicted interference on the primary service.

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Glossary of Terms

3G	3rd Generation
4G	4th Generation
AB-OSA	Access-Bounded- Opportunistic Spectrum Access
AB-IL-OSA	Access-Bounded-Interference-Limited-Opportunistic Spectrum Access
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLER	Block Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
BSC	Base Station Controller
CDMA	Code Division Multiple Access
CR	Cognitive Radio
CU	Cognitive User
CSI	Channel State Information
DARPA	Defence Advanced Research Projects Agency
DS	Direct Sequence

DS-CDMA	Direct-Sequence Code Division Multiple Access
FCC	Federal Communication Commission
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
GoS	Grade of Service
GSM	Global Systems for Mobile Communications
IL-OSA	Interference-Limited-Opportunistic Spectrum Access
INR	Interference power-to-Noise Ratio
MAI	Multiple Access Interference
MIP	Multipath Intensity Profile
MRC	Maximal Ratio Combining
MSC	Mobile Switching Centre
MUI	Multi User Interference
OFDM	Orthogonal Frequency Division Multiplexing
OSA	Opportunistic Spectrum Access
PER	Packet Error Rate
PHY	Physical
PN	Pseudo-Noise

PSTN	Public Switched Telephone Network
QoS	Quality of Service
RNC	Radio Network Controller
RRM	Radio Resource Management
SIR	Signal-to-Interference Ratio
SNR	Signal-to-Noise Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
WCDMA	Wideband Code Division Multiple Access
XG	Next Generation Communication

List of Publications

Journal Papers

1. **Mohammad Mirtavoosi Mahyari**, Arman Shojaeifard, Mohammad Shikh-Bahaei, "Joint Power and Rate Optimization in Shared-Spectrum CDMA Networks," *IEEE Transaction on Mobile Computing, Under Review.*
2. **Mohammad Mirtavoosi Mahyari**, Arman Shojaeifard, Mohammad Shikh-Bahaei, "Probabilistic Optimization of CDMA-based Cognitive Radio Networks," *IEEE Wireless Communications Letter*, *Under Review.*

Conference Papers

1. **Mohammad Mirtavoosi Mahyari**, Mohammad Shikh-Bahaei, "Joint Optimization of Rate and Outer Loop Power Control for CDMA-based Cognitive Radio Networks," *Computing, Networking and Communications (ICNC)*, pp. 392-396, Feb. 2012.
2. **Mohammad Mirtavoosi Mahyari**, Mohammad Shikh-Bahaei, "Impact of Primary Users Activity on Achievable Average Spectral Efficiency of CDMA-based Cognitive Radio Networks," *Wireless Advanced (WiAd),* pp. 181-186, Jun. 2012.

Papers not Included in this thesis

1. Arman Shojaeifard, **Mohammad Mirtavoosi Mahyari**, Mohammad Shikh-Bahaei, "Jointly PHY-layer and DLC-layer Design and Optimization in Multi-Service Networks," Res*ubmitted to the IEEE Wireless Communications Letters.*
2. Arman Shojaeifard, Hadi Saki, **Mohammad Mirtavoosi Mahyari**, Mohammad Shikh-Bahaei, "Cross-Layer Design for Supporting Heterogeneous Traffic in Multi-Service Networks" *Submitted to the Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC).*

Chapter 1

1. Introduction

Wireless communication has experienced significant expansion since the early 1980s and it is now the fastest growing section of the communication industry. This is mostly due to the fact that wireless communication is one of the best means of addressing the accelerating demands for instant and extensive access to information. Wireless communication has also revolutionized the dynamics of the working environment and workforce mobility because people are no longer tethered to a fixed location or formal work-based environment. Research and development in this field in the past decade has made it possible for people to experience a very high data rate and reliable wireless communication. However, wireless communication poses specific challenges. In wireless communication networks, the characteristics of the channel appear to change randomly with time and frequency and these in conjunction with user mobility, making radio-resource allocation a difficult task. Moreover, the growth of wireless applications and multimedia services in current and future heterogeneous networks will require more efficient management of the radio frequency spectrum. In addition, the radio spectrum, as a precious limited resource, must be allocated to-wide range of networks and this has caused the frequency-allocation table for wireless services to become saturated. To tackle the aforementioned problems, it is vital to develop transmission and spectrum-sharing methods for improving efficient utilization of available radio resources. In shared-spectrum environments, the under-utilized parts of the spectrum can be exploited by other networks users. The main focus of this thesis is on adaptation of transmission parameters with the aim of improving performance and reducing the cost of each correctly delivered information bit, in a shared-spectrum environment.

Prior to highlighting the aim of this thesis and reviewing its objectives and contributions, this chapter introduces the area of research by stating the fundamentals of cellular wireless systems, radio resource management, adaptive resource allocation and cognitive radio technology.

1.1 Cellular Mobile Networks

A cellular network consists of a number of fixed base-stations (BSs) arranged to provide coverage of mobile users as long as they are within the operating range of the BS. The total geographic region in cellular systems is divided based on the operating range of a BS into small segments, called cells and each mobile user communicates with the closest BSs. Each mobile user is assigned with a radio channel for communicating with the BS. The BSs in a given area are connected to base-station controllers (BSCs), and BSCs are connected to a mobile switching centre (MSC) by high-speed wire connections or microwave links, and finally the MSC is connected to the public switched telephone network (PSTN). A technique called handover is employed for avoiding call interruption or termination when a mobile user moves from one cell to another by switching the serving BS. The wireless link from a BS to the mobile users is called the downlink and the link from the users to a BS is called the uplink. In addition, system resources can be simultaneously separated between the uplink and downlink based on two basic strategies, frequency division duplex (FDD) and time division duplex (TDD). In FDD each mobile user is provided with two separate radio transmission frequency channels for uplink and downlink communications, and TDD uses a single radio channel but the uplink and downlink transmissions shared in this channel in time.

1.2 Multiple Access Principles

Frequency spectrum is a naturally limited resource and one solution to overcome the scarcity of this limited commodity in wireless systems is to share resources among users in cellular systems to accommodate several mobile users simultaneously and achieve higher user capacity. Radio resources sharing among mobile users can be done by employing one of number of multiple-access techniques. In principle, there are three basic methods to divide the allocated Radio resources into many channels and then assign these channels to different users: frequency, time or code. These methods are addressed by three multiple access techniques, that is, frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA).

In FDMA, the radio spectrum is divided into non-overlapping orthogonal frequency band, and each user is assigned a different frequency band for transmission. The concept of FDMA is shown in Fig. 1.1. The guard channels are considered between two adjacent frequency bands to compensate for imperfect filters and adjacent channel interference. In FDMA, users cannot share the frequency band at the same time and also a single user cannot use multiple channels for transmission. These, along with inefficiency caused by wasting some parts of the spectrum by assigning guard channels are the main disadvantages of FDMA.

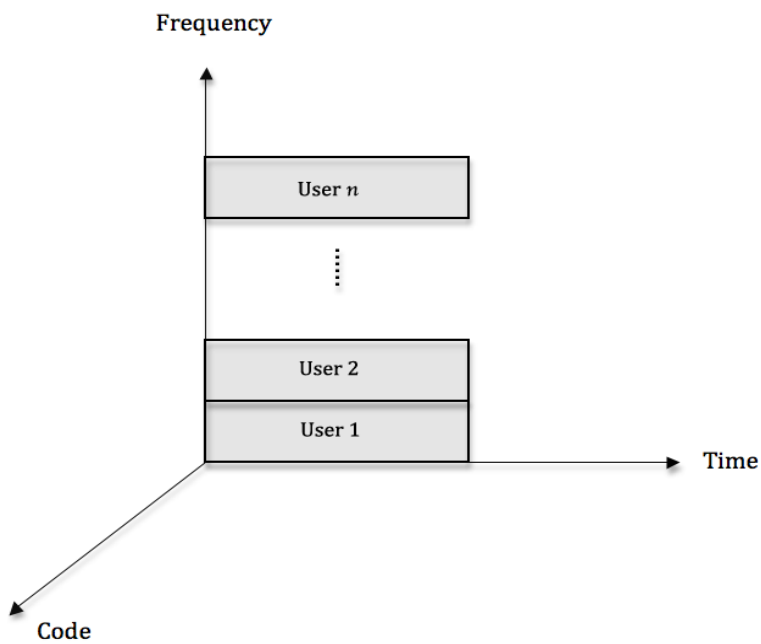

Figure 1.1: Frequency division multiple access (FDMA)

TDMA splits the transmission time into several time slots, where each slot is only allocated to one user at a time. In TDMA, a frequency band can be efficiently utilized by multiple users as each user uses different time slot for transmission. The second generation digital cellular networks such as Global Systems for Mobile Communications (GSM) [54], introduced in the late 1980s, pioneered TDMA. Fig. 1.2 displays the structure of TDMA. The main advantage of TDMA is that assigning a single user with multiple channels is simple and can be done by allocating multiple timeslots. A major difficulty of TDMA is the needs for synchronization among all users. Furthermore, it requires guard times between time slots to cope with synchronizations errors and minimize transmission time delay.

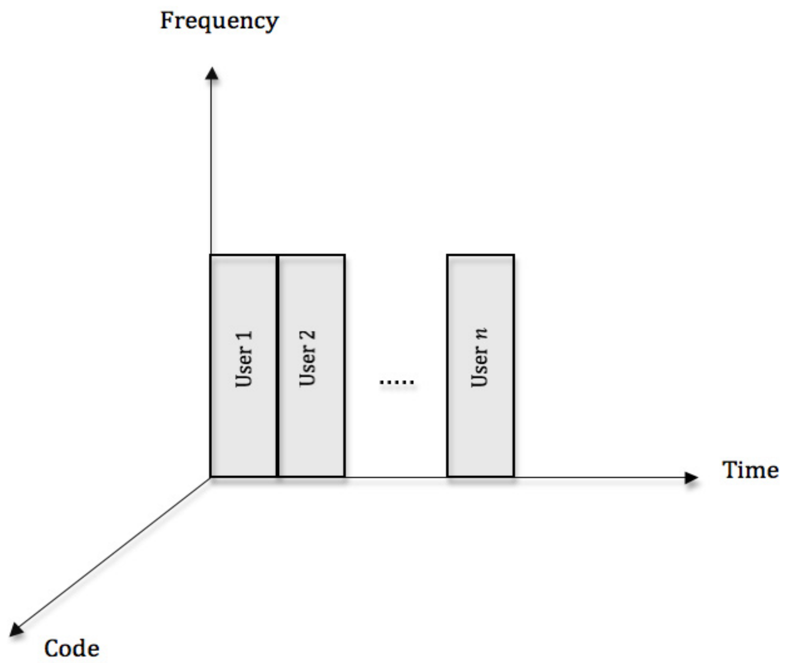

Figure 1.2: Time division multiple access (TDMA)

In CDMA, each user is assigned with a spreading code and the information signals of that user are modulated by the selected spreading code. Consequently, multiple users can share a common channel in frequency and time, as shown in Fig. 1.3. A CDMA system is based on spectrum-spread technology, which is a family of technologies originally devised for military communications in the 1950s [73]. In CDMA, the narrowband message signal is multiplied by a very large bandwidth signal called the spreading signal. CDMA can also support a high number of users proportional to the spreading factor. The ratio between transmission bandwidth (spread signal) and original bandwidth (bandwidth before spreading) is called the spreading factor (also referred to as spreading gain). A CDMA scheme also requires power control to compensate for the near-far effects, whereby received signal at the BS from far-away users could be masked by a signal from users close to the BS.

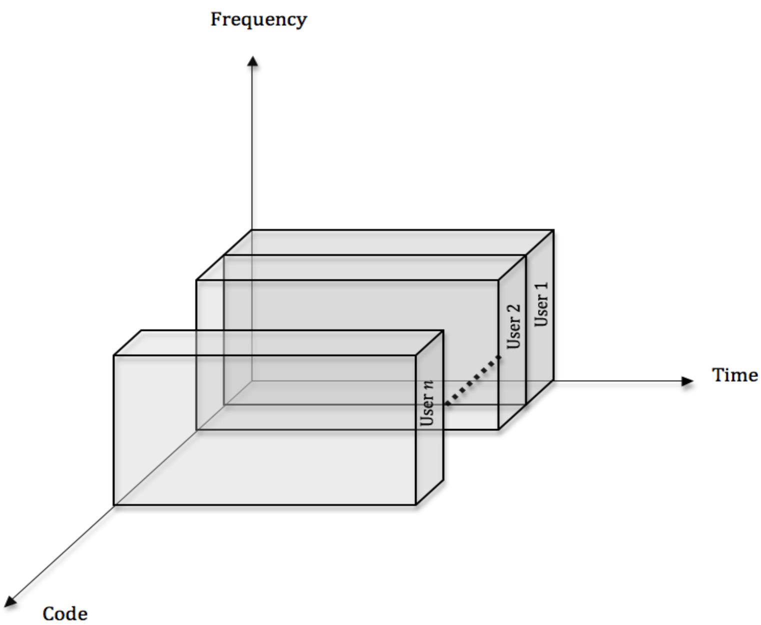

Figure 1.3: Code division multiple access (CDMA)

The most common form of CDMA is multiuser spread spectrum with either direct-sequence (DS) or frequency-hopping (FH) [21]. In DS-CDMA, the user data signal is multiplied by a unique pseudo-noise (PN) spreading code sequence. At the receiver, the received signal is despreaded by correlating it with a spreading sequence identical to and in synchronization with the sequence used at the transmitter for spreading the signal. In

FH-CDMA, the radio signal frequency band is changed by using a pseudorandom sequence across a broad frequency band in a random fashion. The carriers are hoping from one frequency to another in predetermined but pseudorandom manner. The pseudorandom spreading sequence is known to both the transmitter and the receiver.

Wideband CDMA [3,14,48] (WCDMA), a major third generation (3G) radio access, employs DS-CDMA as a multiple access technique and requires a minimum spectrum allocation of 5 MHz. WCDMA can support a large number of mobile users with high data rates. The first commercial WCDMA network was launched in 2001 by NTT DoCoMo in Japan.

1.3 Capacity and Spectral Efficiency

Information theory was founded by Claude Shannon in late 1940s to discriminate the limits of reliable communication. The capacity of the channel is defined as the maximum amount of data that can be transmitted over a wireless channel with arbitrarily small error probability. His mathematical model was based on the notion of the mutual information between the input and output of the wireless channel, maximized over all possible input distributions. The capacity of CDMA systems is limited by interference [20]. The number of active users in CDMA systems is limited by multiple access interference (MAI) or multi user interference (MUI).

The amount of data bits that can be successfully transmitted over a given frequency spectrum is called spectral efficiency. It can be used to measure the capability of the network to efficiently utilize dedicated limited bandwidth. Spectral efficiency is measured in terms of spatial traffic density per unit bandwidth [79]. The link spectral efficiency in cellular wireless systems is measured in Erlangs per Hertz per cell (Erlangs/Hz/cell) or bits per second per Hertz per cell (bit/s/Hz/cell). This thesis concentrates on maximizing spectral efficiency of the cognitive network by employing adaptive resource allocation techniques in the presence of Quality of Service (QoS) requirements.

1.4 Radio Resource Management

Due to the limited availability of wireless radio resources, it is essential to adopt a strategy for maximizing spectral efficiency of a system by allocating these resources to users for delivering the best QoS at the lowest cost. Radio resource management (RRM) algorithms and strategies are employed to increase spectrum efficiency by controlling parameters such as transmit power, data rate, handover criteria and scheduling. Therefore, the objective of RRM is to improve efficient utilization of bandwidth by increasing spectral efficiency under pre-set grade of service (GoS) constraint. Scarcity of frequency spectrum and increasing demand for high data rates have made RRM an area of active research. The focus of this thesis is on transmission power control and transmission rate control mechanisms in shared-spectrum wireless communication networks.

1.4.1 Transmission Power Control

Interference imposed on mobile can significantly degrade mobile communications performance. Power control is adopted by wireless systems to minimize the interference level in the air interface and to provide the required QoS for all mobile users. From the point of any cellular network, accurate power control is helpful for minimizing the interference level while optimizing spectral efficiency of mobile users. In power control techniques, transmit power is assigned to each user in a way that satisfies their QoS requirements while transmitting with the least amount of power. Consequently, transmit power can reduce consumption of the limited energy available in the battery of a portable device. Power control is mainly used in uplink transmissions as the BS has continuous access to power from the mains outlet. The user capacity in DS-CDMA is adversely affected by the near-far problem, thus accurate and tight power control of all mobile users in the system is an essential and an added challenge for transceiver design.

In general, in narrowband and in wideband CDMA there are two different power control techniques, i.e. open loop power control and closed loop power control. The former is used to provide a coarse initial power setting of the mobile station at the beginning of a connection. The latter commands the mobile station to use a transmit power proportional to the inverse of the received power. The closed loop power control is a combination of fast inner loop power control and outer loop power control. Power control strategy is used in uplink communication for minimizing the uplink power of all mobile users and balancing the signal-to-interference ratio (SIR) of mobile users obtained at the BS.

The fast inner loop is done based on the level of received SIR. The base station performs frequent estimates of the received SIR and compares them with a target SIR. If the measured received SIR is lower than the SIR-target value, a command will be sent to the mobile user by the BS to transmit at higher power; if it is too high, the mobile user will be commanded to decrease its transmit power. Thus, the effect of this type of control is that the received power is maintained constant for all condition of the channel so as to achieve the SIR-target. In WCDMA the power control step-size is usually fixed at 1 dB [27].

A SIR-target is set by the outer loop power control to meet the QoS requirements and used by inner loop power control. Practically, outer loop power control is used to provide the required transmission quality, which is generally defined in terms of the bit error rate (BER) or block error rate (BLER), by accurately setting the SIR-target. The general algorithm of the outer loop power control is illustrated in Fig 1.4. The outer loop power control is also known as slow closed loop power control as its execution frequency in WCDMA is 10-100 Hz, whereas, fast inner loop is executed at 1500 Hz. This thesis focus is on inner loop and outer loop power control strategies.

There is close relation between SIR and effective transmission rate that makes power control a practical technique for altering data rates. Such a connection develops an interest in studying transmission power control and transmission rate control jointly.

Figure 1.4: Outer loop power control algorithm

1.4.2 Transmission Rate Control

Future heterogeneous networks are expected to support traffic with diverse bandwidth and it is necessary to perform multiple-rate transmission. This makes transmission power control a complex task. One possible method for assigning data rates to mobile users is to relate data rates to SIR-target. It can be assumed that there is an access to infinite number of SIRs and transmission rates resulting in a continuous relation between them. Otherwise, if instead the number is limited the relationship is discrete. In DS-CDMA systems, a trade-off between transmitting date with lowest possible power and achieving a highest data rate must be attained. Therefore, the SIR-target is raised to maximum allowed by the power constraint with the intention of obtaining higher data rate and satisfies a pre-set error probability. The main objective of this thesis is designing an algorithm for assigning the best SIR-target and rate to mobile users in a cognitive radio (CR) environment.

Due to fluctuations in wireless radio channels it is necessary to use adaptive-rate transmission methods, with the intention of improving utilization of transmission resources by adapting transmission parameters to channel states. One scheme for adaptive-rate transmission implementation is to use variable spreading factor, whereby users dynamically vary their bit durations over a fixed rate chip sequence.

1.5 Adaptive Resource Allocation

The premise of using information of channel characteristics at the transmitter to improve performance of communication systems has been around since at least 1968 [25]. The main concept is to estimate the channel at the receiver and exploit this estimated information at the transmitter to adjust transmission parameters in order to maximize communication performance. The BS estimates the channel gains for all users and selects the users allowed to transmit in each time interval based on the quality of previously received signals or reference signal transmitted in advanced. However, channel estimation errors occur due to noisy estimation in the receiver or channels variation after it has been estimated. Consequently, due to a lack of good channel estimation as well as hardware constraints, this technique could not be implemented in the early days of its introduction. However, as technology evolved these issues became less constraining, resulting in a revived interest in adaptive resource allocation methods for 3G wireless systems [34, 60, 69, 87]. Practically, adaptive resource allocation techniques can be used to enhance spectral efficiency by adaptively varying one or combination of rate, power, code and error probability. In section 2.1, various adaptive resource allocation methods in non-shared spectrum CDMA systems are reviewed.

1.6 Cognitive Radio Technology

Spectrum is naturally a limited and finite resource in wireless technology and one that is regulated by government agencies such as the Federal Communication Commission (FCC) in the United States [77]. Most of today's wireless radio communication systems require precise protection against interference from other radio systems. Consequently, frequency bands are exclusively and entirely licensed to users with obligatory and detailed guidelines. However, such an approach and policies in conjunction with accelerating spectrum-access demand have lead to a shortage of available spectrum. However, the existing radio regulatory regime is too complex to handle the increasingly dynamic nature of emerging wireless applications. In fact, the chart of allocated frequency band shows that there is nearly no spectrum available to offer to future networks [77]. Dynamic spectrum access refers to the time-varying, flexible utilization of the parts of the radio frequency band under restrictions set by regulators. CR technologies together with dynamic spectrum access attempt to overcome the problem of spectrum scarcity. The term CR was first introduced by J. Mitola in [53] as an advanced version of software radio. "CR is an intelligent wireless communication technology that is aware of its surrounding environment (i.e. its outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency stimuli by making corresponding changes in certain operating parameters such as transmit power and modulation strategy in real time [26]". The concept of CR technology is inspired by the Defence Advanced Research Project Agency (DARPA) Next Generation Communication (XG) program [9]. The potential gain of CR technologies is higher utilization of infrequently used spectrum. Dynamic spectrum access and spectrum sharing are two main tools that help regulators to improve efficient utilization of frequency bandwidth.

In CR technologies primary (licensed) spectrum can be exploited by cognitive (secondary) users (CUs) when it is not being used by primary (license holding) users or it can be used simultaneously as long as CUs activity does not cause unacceptable interference to licensed users. Primary users operate with higher priority over CUs, as they are spectrum license holders and have paid a fee for the bandwidth, and their performance should not be degraded by the operation of CUs. CR aims at maximizing efficient utilization of limited frequency spectrum while accommodating the increasing number of services and applications in wireless networks. In CR technologies, the unused part of the frequency band is identified by the CUs and utilized in and intelligent way based on spectrum observation. Such an unused part of the spectrum is called spectrum opportunity, as shown in Fig 1.4. CR techniques provide the capability to use or share the wireless frequency band in an opportunistic manner. Opportunistic Spectrum Access (OSA) refers to CR technique that allows the CUs to dynamically detect and exploit the part of primary spectrum that is either not-utilized or under-utilized. The aim of employing OSA in spectrum sharing is to enhance the utilization of the allocated frequency band whilst satisfying primary users' QoS requirements.

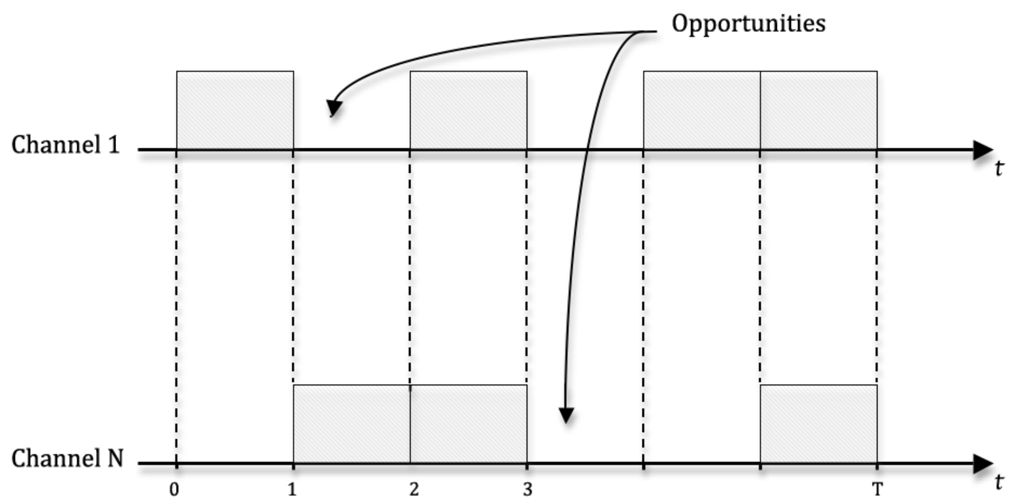

Figure 1.5: Spectrum opportunities in shared-spectrum environment

System designers currently face two contradictory challenges in the spectrum sharing problem. The first is to guarantee the signal quality of primary users as licensed users and the second is to maximize the throughput of CUs. The former implies considering a very low transmit power for CUs, whereas the latter requires a high power allocated to CUs, which can result in a violation of QoS requirements for licensed users. The main focus of this thesis is on achieving a trade-off between the two aforementioned requirements of CR environments. In section 2.2, a number of schemes developed so far for improving the capacity of the CUs and schemes for minimizing their interference on primary users are reviewed.

1.6.1 Interference Temperature

Interference temperature is proposed to control the sources of interference in a radio environment. The specification of an interference-temperature limit provides a worst-case characterization of the radio frequency environment in a particular frequency band and in a particular geographic location. In CR environments, interference temperature at a primary receiver antenna provides a measure for acceptable level of interference (caused by the operation of un-licensed users) in the primary frequency band of interest. Transmission of CUs in the primary frequency spectrum is considered to be harmful if it increases the noise floor above the interference-temperature limit. Interference-temperature limit is set by the primary network in order to satisfy QoS requirements of its own users. The opportunistic transmission behaviour of the cognitive networks imposes unique challenges for their coexistence with primary networks and QoS provisioning of carried services. The cognitive network access to the idle part of the primary spectrum can be categorized into two schemes based on the level of acceptable interference temperature, access-bounded OSA and interference-limited OSA. The former implies no level of interference, caused by the operation of the CUs, can be tolerated by the primary network and that CUs are only allowed to transmit data over the licensed frequency when it is idle. The latter indicates that the licensed frequency band can be simultaneously utilized by both primary and cognitive users subject to non-violation of the acceptable level of interference set by the primary network. In interference–limited-OSA (IL-OSA), the primary network checks the interference caused by the activity of CUs and stops their transmission when interference exceeds the pre-set limit; whereas, in access-bound-OSA (AB-OSA), CUs can only utilize shared-spectrum when it is not being used by the primary users. Therefore, CUs should detect spectrum opportunity in frequency, time or even code, by observing the licensed spectrum. An availability of spectrum opportunity can be obtained from spectrum sensing.

1.7 Thesis Aim and Organizations

The main aim of this thesis is to enhance the efficient utilization of the spectrum as it is a limited precious resource. Therefore, this thesis integrates adaptive resource allocation techniques into a shared-spectrum problem. This thesis concentrates on RRM techniques for maximizing cognitive network spectral efficiency by means of exploiting the flexibility of OSA and adaptive transmission techniques. Therefore, the aim is to develop resource allocation algorithms for enhancing the performance of the CUs that utilize the licensed spectrum. There is consideration of multi-user DS-CDMA primary and cognitive networks and investigation of the performance for the uplink transmission. Investigations concentrate on physical (PHY) layer resource allocation. This thesis is organized as follows:

In Chapter 2, relevant studies undertaken in the field of adaptive resource allocation and spectrum sharing are reviewed. Each of this works has, to some extent, inspired this PhD research. A description of a number of adaptive resource allocation schemes in non-shared spectrum environment is developed. This is followed by a review of a number of methods for improving the utilization of the radio spectrum in a shared-spectrum environment.

Chapter 3 makes several contributions. Shared-spectrum system is considered where both primary and cognitive networks use CDMA technology for data transmission. A CR technology is used by the CUs to exploit part of the primary air interface resources subject to non-violation of QoS requirements of the primary network. Considerable gain can be achieved in CUs' throughput by allowing them to share the licensed bandwidth with primary users. This gain is further enhanced by using joint optimization of closed loop power control and rate control. A closed-form expression is obtained for the CUs' optimal outer loop signal-to-noise-ratio- (SNR-) target. The main goal of this chapter is to maximize the average spectral efficiency of the CUs and simultaneously keep the interference introduced by their operation below the threshold set by the primary network. The IL-OSA system is considered; hence CUs can exploit the licensed spectrum concurrently used by the primary users subject to compliance with the interference threshold. The system performance is investigated under the peak and average received-interference and under Nakagami-m frequency-selective fading channel. A novel technique is introduced for adapting the level of acceptable peak threshold to the number of active users (primary and cognitive) in the primary network. This chapter is partly based on [49] and [50].

In Chapter 4, a method is introduced for the optimization of the CUs spectral efficiency, based on the activity of the primary users. In this chapter AB-OSA system is considered thus and the primary network does not tolerate any interference from the CUs. Therefore, CUs are only allowed to transmit data over the shared frequency band when the activity of the primary network is lower than the pre-set threshold. CUs thus utilize the cognitive network frequency band and seek an opportunity to exploit the primary bandwidth by using the spectrum-sensing technique. The main goal is to determine the gain that can be achieved by employing OSA technique in the CR environment. The average spectral efficiency of the reference CU that uses a joint optimization of the close loop power control and spreading factor are studied. The idea for the work in this chapter stems from [51].

In Chapter 5, a novel method is proposed that exploits a combination of AB- and IL-OSA (AB-IL-OSA) schemes to guarantee QoS requirements of the primary network, and simultaneously adaptive transmission is used to enhance achievable spectral efficiency of the CUs. In CDMA/CDMA share-spectrum system, primary resources are shared both in time and frequency. The proposed scheme can meet the tightest QoS requirements of the primary network at any time. This can be done by stopping CUs transmission when the primary network becomes saturated and keeping the level of CUs interference below the pre-set limit. The research in this chapter leads to [52].

Chapter 2

2. Relevant Previous and Parallel Works

The main research focus in the spectrum sharing communication area is on maximizing the CUs' capacity and minimizing the interference inflicted on the primary users. The CUs' throughput optimization is mainly done by utilizing adaptive resource allocation techniques while different access protocols are used by the CUs for limiting the interference received at the primary network. Adaptive transmission in CDMA systems involves varying either one or a combination of transmission power, modulation level, processing gain, chip rate, number of spreading code and coding scheme or rate, with the aim of maximizing the efficient utilization of limited bandwidth. Therefore, the overall design objective of CR systems is to maximize efficient utilization of the frequency spectrum and CUs' throughput while protecting primary users from the interference caused by the operation of CUs in shared bandwidth. To satisfy the transmission requirements of current and future heterogeneous systems, efficient adaption algorithms are essential in the CR environments.

The emphases of this thesis are maximizing the CUs' spectral efficiency and minimizing the amount of interference caused to the primary network receiver. The optimization of the CUs' spectral efficiency is done by exploiting the joint optimization of power and rate technique and interference limitation is done by using different OSA techniques. The rest of this chapter is structured as follows. First, the literature behind adaptive transmission techniques mainly in non-shared-spectrum systems is outlined. Second, relevant previous and parallel works in shared-spectrum CR environments is reviewed. As the research in these areas has been extensive, only the most relevant work is touched up throughout this chapter.

2.1 Adaptive Transmission Techniques

The importance of efficient power control algorithms for solving the near-far problem and to enhance capacity has been widely addressed in [19, 84, 85]. The following paragraphs review some of the work done in the area of fixed-transmission-rate power control.

Early work on quality based power control was performed by Bock and Ebstein [11] in 1964. They formulated the power assignment problem as a linear programming problem. The problem of SIR-balancing for spread spectrum systems without background noise was considered by Alavi and Nettleton [4], and they showed a significant improvement in capacity. Knopp and Humblet [42] developed a power control scheme that maximizes sum capacity of the uplink channel in single-cell multiuser communication with arbitrary fading statics. Moreover, Holtzman showed that power control for certain user is waterfiling in time [28], i.e., more power is allocated for a fraction of time that condition of the channel is good (the received power is high) and less when the channel condition is poor.

Authors in [88] analyzed the performance of the multimedia CDMA network that support voice and data traffics each having different data rate and packet error rate (PER) requirements. In multimedia systems, the power control method is used not only for solving the conventional near-far problem, but also the near-far effect caused by the natural dissimilarity (such as data rate and PER) between different traffics being transmitted through the same channel. Kumar *et al.* [44] proposed an algorithm for power control based on the BER measurements requirements rather than SIR measurements. The objective of their proposed algorithm was to achieve a pre-set BER with minimum possible transmission power and it does not need any explicit knowledge about the relationship between the BER and the SIR. Their proposal algorithm just uses the general expression, $R = \exp(-SIR)/2$, which is encountered in digital communication for high SIR scenarios.

Most of the proceeding power control algorithms in the literature are constructed under the assumption of perfect power control, i.e. considering that the BS can maintain the received power such that the received SIRs are constant. However, in practice, fading environments cause a number of limitations such as power control errors and implies imperfect power control [2, 23, 65, 70, 71], and the received SIR of each user becomes a random variable, therefore, complicating the task. Randomised nature of the received SIRs in fading environments was examined by Hashem and Sousa [24] and Shu and Niu [74]. In multimedia communication systems, another source of randomness of SIRs is the burstiness of traffic, therefore, the number of active users must be considered as a random variable [39, 45, 62, 74].

By far, most of the above work consider only the inner loop power control issues in their proposed SIR-balancing algorithms and outer loop power control is usually neglected, by assuming a constant SIR-target[23, 59, 76], or perfect estimation of the SIR [89]. However, for improving the spectral efficiency and the system throughput the SIR-target must be adapted to the channel state in fading environments. A number of works examine the performance enhancement achieved by using the optimal outer loop power control [7, 35, 43, 58].

In wireless communications, transmission power and transmission rate are two important resources which should be well controlled to achieve different objectives such as reducing total transmitting power and increasing the system total throughput. It is advantageous to associates the transmission rate control with transmission power control as they are both related to the SIR. The early studies on adaptation of transmit power and rate to channel fading conditions was done by Hayes [25] in 1968.

Goldsmith and Varaiya [22] considered a fading channel and determined the capacity with an average power constraint by applying waterfilling in the time domain for power and rate. Their results confirm the common observation that allocating resources to good channel maximises total system throughput. They proved that for independent and identically distributed (i.i.d) channel fading, adaptation at both the transmitter and the receiver does not enhance the capacity or decrease the coding complexity comparing to the system that uses adaptation at the receiver only. They also considered channel inversion and truncated channel inversion suboptimal adaptation schemes, which adapt the transmit power but keep the transmission rate constant.

The transmit power is adjusted to invert the channel power gain in the total channel inversion policy, for example, for a gain of $g(t)$, the transmit power is adjusted to $\sigma/g(t)$, where σ is the target received power [19, 22, 85]. However, it can exhibit a large capacity penalty in extreme fading environments, where a large transmit power is needed. The truncated channel inversion policy, however, compensates for a fading above a pre-set cut-off threshold. The truncated channel inversion policy combines the advantages of waterfilling and channel inversion schemes by stopping the transmission of inferior channels. Kim and Goldsmith [40] and Kim and Lee [41] analyzed the performance of the truncated channel inversion strategy. Authors in [40] showed a gain both in the maximum capacity and the power relative to the conventional policy. Their work confirms that truncated channel inversion is the most effective policy for channels with large power fluctuations or large amount of background noise.

Authors in [72] and Ramakrishna and Holtzman [68] used adaptive spreading factor and transmission power control subject to minimum transmission rate, maximum average transmission power and SIR-target constraints. The authors in the former reference considered a dual-class CDMA system and proposed a scheme for maximizing the uplink channel throughput, where one of the classes is delay-sensitive and needs only a constant bit rate, while the other class is delay-tolerant and aims to have a larger variable bit rates. In their proposed scheme, no constraint is imposed on the peak transmit power of users and their scheme achieved a considerable gain while the delay requirements of all user is satisfied. Yang and Hanzo [91] proposed a scheme that uses a variable spreading factor for adapting transmission rate to the level of MAI. They considered constraints on average transmit power and BER, and their proposed scheme enhanced the system throughput by up to 40%.

Jafar and Goldsmith [29] proposed an adaptive rate and power control algorithm for maximizing the throughput in a multirate CDMA system. They showed that the optimal spectral efficiency can be attained if a user transmits only when all users with a better channel are transmitting at their maximum rate. The authors used a discrete set of rates and their results confirm that the optimal average throughput does not increase significantly if more rates are available for a fixed range of rates. The extension to continuous-rate adaptation was done in [30]. Here, the QoS constraints are neglected and the throughput upper bound is derived. Their numerical results confirm that the throughput of the optimum rate and power adaptation scheme is very close to an adaptive-rate with fixed transmit power scheme. On the other hand, the optimum power adaptation scheme with fixed-rate yields considerably lower throughput.

This thesis proposes an adaptive resource allocation technique for maximizing the cognitive network throughput in shared-spectrum environments. The proposed scheme involves joint optimization of power and rate control using variable spreading factor. The next section reviews the most relevant previous and parallel work in the area of CR.

2.2 Cognitive Radio

The basic components of OSA in shared-spectrum systems are opportunity detection, spectrum opportunity utilization and regulatory policy. The opportunity detection module is responsible for monitoring the primary frequency band and identifying the un-utilized or idle parts of the primary licensed frequency band. The spectrum utilization module is in charge of deciding how to transmit the data over the primary spectrum to maximize the CUs' throughput, based on access technique used by the CUs. The regulatory policy defines the basic protocols for the CUs to ensure that their operation does not violate the primary users' QoS requirements.

The performance in cognitive communication networks depends on careful resource allocations such as bandwidth allocation and transmission power control. Asghari and Aissa [5] proposed an optimal time-sharing and power allocation policy to maximize the achievable capacity of fading CR broadcast channels. Authors in [55] considered a shared-spectrum CR system and obtained the optimal power allocation strategies to achieve the channel capacity, and derived closed-form expression for the capacity metrics under Rayleigh fading. Authors in [81] proposed an adaptive-power-control scheme for a CR system in Rayleigh fading channel. They showed that the CUs' throughput is maximized by maintaining a constant output power at the cognitive network receiver using power adaptation at the cognitive network transmitters. Da and Ko in [13] proposed an algorithm for improving the efficient radio resources allocation in CR systems. Their proposed solutions are partial distributed algorithms that can dynamically allocate resources to the CUs so the capacity of the cognitive network can be maximized. The authors in [12], [32] and [93] focused on the problem of maximizing the utilization of the spectrum opportunities in CR networks with multiple potential channels and developed an optimal strategy for OSA. Srinivasa and Jafar [78] characterized a trade-off between system sum throughput (both primary and cognitive networks) maximization and primary user interference minimization and identified the optimal amount of spectrum sharing that maximizes the total system throughput.

Interference is one of the biggest challenges to overcome when considering CR networks. To a great extent, two main OSA access techniques are used in the literature; IL-OSA or underlay and AB-OSA or overlay. In IL-OSA scheme the CUs could concurrently access the primary radio spectrum even during the presence of the primary users, provided that the activities of the CUs do not cause intolerable interference (or harmful interference) towards the primary users [26, 47, 90]. In AB-OSA, the CUs could use that primary bandwidth during the absence of the primary users [47]. Authors in [31] proposed a protocol in which the CUs listen to the wireless channel to determine which part of the licensed spectrum is unused so as to adapt their signal to fill the unused spectrum domain.

In AB-OSA technique, the CUs should check the availability of primary frequency band and only utilize it when it is un-utilized. The authors in [61] and [80] characterized the channel availability by a two-state Markov chain. Although being very simple, this model is able to capture the temporal characteristics of the channel availability in an OSA system. However, Zhou and LI [94] used the probabilistic information of channel availability obtained from spectrum sensing to assist resource allocation in CR networks, which exploits the flexibility of OSA and has better performance compared with conventional approaches based on the hard decisions on channel availability. Motivated by the concept of spectrum sensing, the authors in [46] studied the trade-off between channel sensing and the CUs' throughput considering the Shannon capacity as the throughput metric. They formulated an optimization problem and identified the optimal sensing time which leads the highest throughput for the CUs while providing sufficient protection in terms of interference to the primary users.

Information about the availability of the channel may be obtained through either local or cooperative spectrum sensing. Authors in [63], designed a power allocation strategy for maximizing data rate of the CUs using both cooperative and non-cooperative spectrum sensing. Better performance was achieved by using a cooperative spectrum sensing in comparison to a system that uses non-cooperative spectrum sensing. Ghasemi and Sousa [16] analyzed the performance of cooperative spectrum sensing in fading environments and studied the effect of collaboration between the CUs in the shared-spectrum environment. They showed a significant performance enhancement can be achieved by using cooperative spectrum sensing. Authors in [17] analyzed the performance of spectrum-sensing radios under channel fading. They proved that due to uncertainty resulting from fading, local spectrum sensing alone may not be adequate to meet performance requirements. Therefore, to remedy this uncertainty they also focused on the cooperation among CUs and the trade-off between local processing and cooperation in order to optimize the shared-spectrum exploitation.

In IL-OSA access scheme, the CUs can utilize the primary radio frequency subject to interference constraint specifies the maximum interference power level. Interference or received-power constraints are set to satisfy the QoS and GoS requirements of the primary users. Consequently, the CUs should keep the interference, caused by their operation in the primary frequency band, inflicted on the primary receiver below the interference threshold. Authors in [18] proposed an IL-OSA system and investigated the capacity gains offered by this dynamic spectrum sharing approach when channels vary due to fading. In their proposed system, the CUs take advantage of the fading environment by opportunistically transmitting with high power when their signal, as received by the receiver of primary network, is deeply faded. Authors in [8] studied the impact of interference threshold constraint on the achievable capacity of the CUs. In [6], Asghari and Aissa, studied two adaptation policies at the CUs' transmitter in a CR system under constraint on average interference caused at the primary receiver over Rayleigh fading channels, one of which is variable power and the other is variable rate and power.

By far, most of the research in literature, focused on maximizing the CUs' throughput in IL-OSA systems subject to the average received-interference constraint. Therefore, there has not been much attention paid to the CUs' capacity subject to both average and peak received-interference constraints, although its importance has been known for decades [75]. Practically, considering an average received-interference is reasonable when the primary users' QoS is determined by average SNR; however, in many situations the primary users' QoS would be limited by the instantaneous SNR at the receiver which renders a peak interference constraint more appropriate. Limiting the CUs' transmit power by considering a more restrictive peak received-interference is a better option from the perspective of protecting the primary users. However, such a constraint has less flexibility for dynamically allocating transmit powers over different fading states compared to the average received-interference and consequently reduce the CUs' capacity. Hence, a trade-off can be achieved by considering joint average and peak received-interference constraints.

Considering a joint peak and average constraints can practically guarantee the QoS requirements of the primary users at any instant, and in addition to allowing the CUs to transmit at higher power when it is tolerable by the primary users. Authors in [36] derived the ergodic capacity of discreet-time fading channel with additive Gaussian noise subject to both peak and average received-power constraints. Musavian and Aissa

[56] proposed a CR system that the CUs can utilize the primary frequency band simultaneously with the primary users subject to non-violation of the peak and average received-power at the primary receiver. They derived the maximum capacity of the Rayleigh flat-fading channel by optimizing transmission power. They showed that even on a strict peak threshold constraint setting, the loss in capacity is not significant when a constraint on the peak received-power is applied on top of the average received-power constraint.

IL-OSA and AB-OSA strategies are compared in [37] and [92]. Results in [92] indicate that in the presence of primary users, interference temperature constraint limits the network capacity in the AB-OSA strategy more than its IL-OSA capacity counterpart. Authors in [38] analyzed the achievable capacity of the CUs which employ OSA access strategy over a fading environment based on the primary users' activity. In their proposed AB-OSA scheme, the fraction of time during which the CUs can utilize the primary frequency band is limited based on the activity of the primary users; whereas in IL-OSA the primary network activity reflects itself in the interference threshold level. They showed a higher capacity can be achieved by using the IL-OSA strategy when a high number of primary users utilize the licensed frequency band. They also showed that the activity of the primary users has a great impact on the CUs' throughput, so less active primary network results in more achievable capacity for the CUs.

Chapter 3

3. Power and Rate Optimization in Shared-Spectrum CDMA Networks

3.1 Contributions

At this point, the contributions of this chapter are highlighted. This chapter will develop:

- A new adaptive transmission scheme in shared-spectrum CR networks.
- Enhancement in the achieved gain in CUs' throughputs, which is attained by using the CR technology, through jointly optimizing the rate and SNR-target of the reference CU.
- A method for satisfying the primary network QoS by considering a limit on peak and average received-interference.
- An optimal trade-off between CUs' throughput and QoS of primary user by dynamically setting of the peak threshold according to the number of active users in the primary network.
- A comparison between systems that use a non-optimal SNR-target and the system that uses the proposed joint optimization scheme.

In parallel, under total channel inversion power adaptation policy, it derived:

- A closed-form solution for the optimal SNR-target, using the matched-filter detector.
- The optimal spreading factor for transmission, using the matched-filter detector.

- A maximum average spectral efficiency of the reference CU, for a case that its transmission power is limited by average received-interference.
- A closed-form expression for the maximum average spectral efficiency of the reference CU, considering both peak and average received-interference constraints under Rayleigh fading conditions and for a case that Nakagami index is $m = 2$.
- A closed-form expression for the maximum average spectral efficiency of the reference CU, for a case that the peak interference threshold is set dynamically based on the number of active users in the primary network.

3.2 Introduction

In this chapter, a novel technique is introduced for enhancing the efficient utilization of the bandwidth in shared-spectrum CDMA networks. The proposed CR network consists of two adjacent conventional DS-CDMA cells, where CUs exploit the primary licensed spectrum subject to not violating the average and the peak received-interference constraints imposed by the primary network. The proposed scheme exploits joint optimization of outer loop power control SNR-target and transmission rate control using variable spreading factors, towards enhancing average spectral efficiency of the cognitive network. The results are extended to the scenario that the maximum tolerable (peak) received-interference is set dynamically based upon the number of active primary users and cognitive users that exploit the primary frequency band.

In this work, a novel adaptive resource allocation technique is integrated into the spectrum sharing problem in CDMA systems. The main goal is to maximize the average spectral efficiency of the CUs while minimizing the interference inflicted on the primary users. The proposed adaptive transmission technique provides the optimization of rate control jointly with closed loop power control. Closed loop power control is carried out through outer-loop and inner-loop schemes, where the fast inner loop power control aims to reach the SNR-target which is set by the outer loop power control, in order to preserve the objective communication quality set in the system design. For a given BER-target, the optimum SNR-target of the reference CU is formulated as a function of the number of active primary and cognitive users. To achieve the SNR-target the transmission rate of the reference CU is adapted to channel conditions using variable spreading factors. These, in conjunction with transmit power adaptation in the inner loop of the CU, lead to a higher achievable spectral efficiency. Hence, the maximum average spectral efficiency is found subject to average received-interference limit caused by the activity of the reference CU at the receiver of the primary network. Subsequently, the performance of the proposed system subject to both average and peak received-interference limits is analyzed.

The performance of the proposed scheme is evaluated over Nakagami-m frequency-selective fading channels with conventional matched-filter detection, under total and truncated channel inversion policies, explained in the next section, in the inner loop. The Nakagami-m distribution spans a range of environments and often gives the best fit to land-mobile and indoor-mobile propagation environments [57]. As m, the Nakagami fading parameter rises, the severity of fading decreases. A novel aspect of this investigation is to analyze the case where the imposed peak-interference constraint is set as a function of the number of active primary and cognitive users that exploit the licensed frequency band.

Considering such a scenario can make the proposed system more reliable by guarantying the QoS requirements of the primary users without the need for conservatively imposing low transmit power limits on the CUs. Moreover, by dynamically setting a peak received-interference temperature the following two factors can be ensured. First, the CUs are allowed to transmit at higher power and consequently achieve a higher average spectral efficiency when small number of active users exploits the licensed spectrum. Second, the use of the primary spectrum by CUs would be limited when a higher number of primary users communicates in the primary network to ensure that the interference, caused by operation of the CUs, does not exceed the threshold set by the primary network during the busy period.

It will be demonstrated in this chapter that by utilizing the licensed frequency band in a shared manner, higher average spectral efficiency can be achieved for the CUs without degrading the primary user's performance. It is also shown that under typical conditions the proposed optimization technique improves the reference CU's average spectral efficiency relative to a system that uses power and rate control but does not exploit outer loop SNR-targets, especially in low SNRs.

The remainder of this chapter is organized as follows. Section 3.3 presents the system model. Section 3.4 provides the definition of spectral efficiency and the considered optimization problem. Section 3.5 analyzes the proposed joint optimization method under average received-interference constraint. The average spectral efficiency of the reference CU under joint peak and average received-interference constraints is derived in closed form in section 3.6. The effect of variable interference temperature on the average spectral efficiency of the CU is evaluated in section 3.7. Numerical results for the performance and the gain achieved through the proposed scheme is evaluated and depicted in section 3.8 and, finally, achievements of this chapter are summarized in 3.9.

3.3 System Model

Suppose $n(t)$ active CUs exploiting communication opportunities within a licensed primary band at time t where, $1 \leq n(t) \leq n_{max}$ and n_{max} is the maximum number of CUs allowed to make use of the primary spectrum at any given moment. Here the CUs term refers to the users that exploiting the frequency belong to the primary network and not all the users in the cognitive (secondary) network. It is also assumed that $k(t)$, $1 \leq k(t) \leq k_{max}$, is the number of the primary mobile users at time t where k_{max} is the maximum number of primary users permitted to transmit data at any time. k_{max} in general is set by the network dynamically based on load control mechanisms. Both primary and cognitive users are transmitting data in the reverse link of the multiuser direct-sequence (DS-) CDMA cellular radio system. The aim is to maximize the average spectral efficiency of a reference CU and the rest of the cognitive and the primary users are treated as MAI. Binary phase shift keying (BPSK) modulation is used and the modulated data is transmitted to the cognitive network base station over a frequency-selective fading channel.

The signal of both primary and cognitive users is spread over a bandwidth B by spreading factor $N(k(t), n(t); P_b)$, where P_b indicates the target bit error probability for both primary and cognitive users. Let $g_{(c_i p)_j}(t)$ and $g_{(c_i c)_j}(t)$ denote the frequency-selective channel gain between the cognitive transmitter i and the primary receiver and the one between the cognitive transmitter i and the cognitive receiver at time t respectively, where $j = 1,..,L_p$ and L_p is the number of paths. The knowledge of $g_{(c_i p)_j}(t)$ and $g_{(c_i)_j}(t)$ is assumed to be available at the cognitive transmitter and receiver. The information about $g_{(c_i p)_j}(t)$ and $g_{(c_i c)_j}(t)$ can be made available by a band manager that mediates between the primary and cognitive users [6], [64], or can be directly fed back from the primary's receiver to the CUs as introduced in [33], which provides an opportunity for the primary and cognitive users to collaborate and exchange the channel state information (CSI). In this work, average spectral efficiency of the reference CU in the presence of k primary users and n CUs is investigated. Therefore, the channel gain between the reference CU and the primary receiver is denoted as $g_{(cp)_j}(t)$ and the channel gain between the reference CU transmitter and the cognitive receiver is signified by $g_{(c)_j}(t)$.

Throughout the transmission zero-mean additive white Gaussian noise (AWGN), $\tilde{n}(\mathrm{t})$, with a two-sided power spectral density of $N_0/2$, is added to the signal. Hence, using Nyquist data pulses,

$$B = \frac{1}{T_{chip}}, \tag{3.3.1}$$

where

$$T_{chip} = \frac{T_b}{N(k(t), n(t); P_b)}, \tag{3.3.2}$$

is the chip duration, and T_b is the bit duration. Given the transmit power of the i-th CU is set to $\bar{S}_i$, the instantaneous received SNR of the i-th CU at the output of the maximal ratio combining (MRC) combiner of the cognitive receiver can be written as [27]

$$\gamma_{c_i}(t) = \frac{\bar{S}_i \sum_{j=1}^{L_p} \left| g_{(c_i)_j}(t) \right|^2}{N_0 B}. \tag{3.3.3}$$

Near-far effect has a considerable impact on CDMA systems, and is commonly controlled by applying dynamic power adjustment schemes so that all users have the same received SNR at the base station. Subsequently, it is assumed that the centralized power control scheme is used in both primary and cognitive networks, hence the subscript i is removed and the average spectral efficiency of the reference CU is derived. Also, the total channel power gain between the cognitive transmitters at the output of the MRC combiner of the primary receiver is set by

$$\left| g_{cp}(t) \right|^2 = \sum_{j=1}^{L_p} \left| g_{cp_j}(t) \right|^2. \tag{3.3.4}$$

Fig. 3.1 shows the schematic diagram of the considered CR system. For brevity and also because $\gamma_c(t)$ and $g_{cp}(t)$ are assumed to be stationary processes, the notion of time t is omitted in the rest of this chapter. With the aim of maximizing the average spectral efficiency, the SNR-target, $\sigma(k, n; P_b)$, is set in the outer loop based on the number of active primary and cognitive users for a given target probability of bit error rate, P_b. The appropriate spreading factor is chosen and the transmit power of the reference CU is adapted to the received SNR at the cognitive receiver, γ_c, in order to attain the SNR-target, $\sigma(k, n; P_b)$. In the remainder of this work the SNR-target, transmission power, variable spreading factor and average spectral efficiency are all calculated for the reference CU.

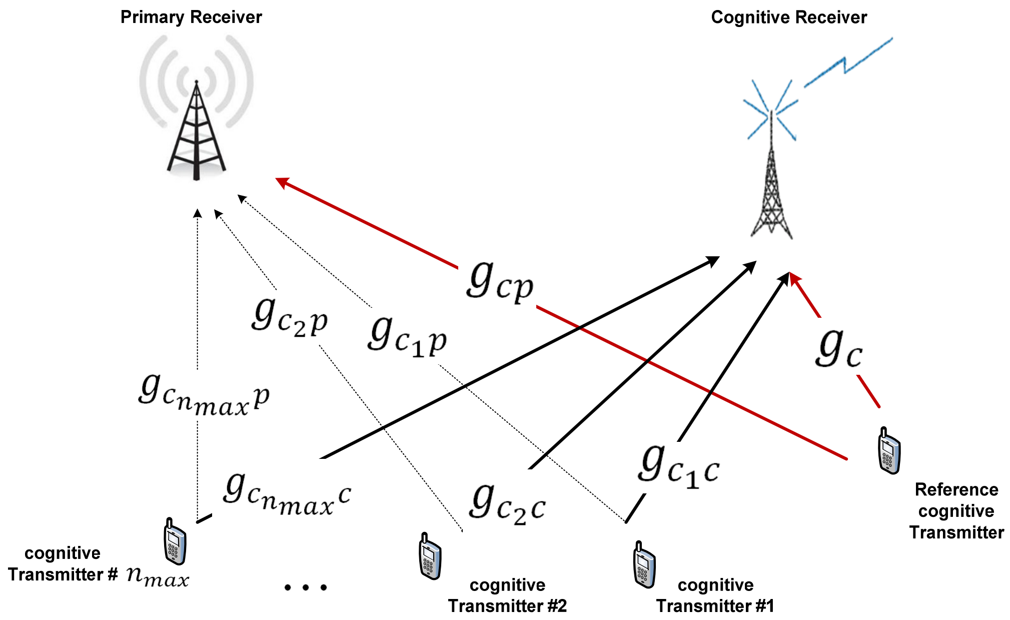

Figure 3.1: System model

Throughout this chapter, both total and truncated channel inversion policies are examined. According to the total channel inversion policy [22]

$$\frac{S(\gamma_c,k,n)}{\bar{S}}=\frac{\sigma(k,n;P_b)}{\gamma_c}, \tag{3.3.5}$$

where $S(\gamma_c,k,n)$ denotes the transmit power of the reference CU. In the truncated channel inversion, transmission is stopped when the channel condition forces the SNR below a given threshold, γ_{c-Th}.

$$\frac{S(\gamma_c,k,n)}{\bar{S}}=\begin{cases}\dfrac{\sigma(k,n;P_b)}{\gamma_c} & \gamma_c>\gamma_{c-Th}\\ 0 & \gamma_c\le\gamma_{c-Th}.\end{cases} \tag{3.3.6}$$

3.4 Spectral Efficiency and Optimization Problem Definition

As mentioned in the previous section, the intention is to show that the proposed scheme can improve the average spectral efficiency of the reference CU subject to average and peak received-interference. Assuming g_{cp} , γ_c, k and n are independent random variables at each instant and their probability density functions are denoted as $f_G(g_{cp})$, $f_\Gamma(\gamma_c)$, $h(k)$ and $r(n)$, respectively. Moreover, let $E_{x,y}[.]$ denotes expectation with respect to x and y.

Evoking $N(k,n;P_b)$ represents the number of chips per bit, the average spectral efficiency of the reference CU, i.e. data rate, R, per unit bandwidth, B, is defined as:

$$\frac{R}{B} = \frac{N_{chip}}{B} E_{k,n}\left[\frac{1}{N(k,n;P_b)}\right], \qquad bits/s/Hz, \tag{3.4.1}$$

where N_{chip} is the number of chips per unit time.

Hence, since k and n are practically independent random variables, it can be assumed that $P_{X,Y}(x,y) = P_X(x)P_Y(y)$. Therefore, the average spectral efficiency can be expressed as:

$$\frac{R}{B} = \frac{N_{chip}}{B} \sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} \frac{1}{N(k,n;P_b)} r(n)h(k), \qquad bits/s/Hz. \tag{3.4.2}$$

The constraint in relation to the average received-interference caused by the activity of the reference CU on the primary receiver can be written as

$$\sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} \int_{g_{cp},\gamma_c} |g_{cp}|^2\, S(\gamma_c,k,n) r(n)h(k) f_G(g_{cp}) f_\Gamma(\gamma_c)\, dg_{cp}\, d\gamma_c \le Q_{\text{avg}}, \tag{3.4.3}$$

where Q_{avg} is the acceptable average interference at the receiver of the primary users.

Using the channel inversion policy expressed in (3.3.5), the maximum of the following objective function can be found as:

$$\max_{\sigma(.,.)} \qquad \frac{R}{B}=\frac{N_{chip}}{B}\sum_{n=1}^{n_{max}}\sum_{k=1}^{k_{max}}\frac{1}{N(k,n;P_b)}r(n)h(k), \tag{3.4.4}$$

subject to:

$$\sum_{n=1}^{n_{max}}\sum_{k=1}^{k_{max}}\int_{g_{cp},\gamma_c}\left|g_{cp}\right|^2\frac{\sigma(k,n;P_b)}{\gamma_c}r(n)h(k)f_G\left(g_{cp}\right)f_\Gamma(\gamma_c)d\gamma_c dg_{cp}\le\frac{Q_{\text{avg}}}{\bar{S}}. \tag{3.4.5}$$

The Lagrangian optimization method is used to derive the optimum SNR-target. The following equation shows the corresponding Lagrangian function:

$$L(\sigma(.,.),\varphi)=\frac{N_{chip}}{B}\sum_{n=1}^{n_{max}}\sum_{k=1}^{k_{max}}\frac{1}{N(k,n;P_b)}r(n)h(k)$$

$$+\varphi\sum_{n=1}^{n_{max}}\sum_{k=1}^{k_{max}}\int_{g_{cp},\gamma_s}\left|g_{cp}\right|^2\frac{\sigma(k,n;P_b)}{\gamma_c}r(n)h(k)f_G\left(g_{cp}\right)f_\Gamma(\gamma_c)d\gamma_c dg_{cp}-\frac{Q_{\text{avg}}}{\bar{S}}, \tag{3.4.6}$$

where φ represent the Lagrangian multiplier.

In the following section the optimum SNR-target and the maximum average spectral efficiency of the reference CU are derived for a case that the reference CU transmission is limited by average received-interference constraint.

3.5 Optimal SNR-target Under Average Received-Interference Constraint

Under multipath fading, the SNR at the output of the cognitive receiver's matched-filter detector can be approximated as [15,67]:

$$SNR = \left\{\frac{q(L_p,\delta)-1}{2N(k,n;P_b)} + \frac{(k+n)q(L_p,\delta)}{3N(k,n;P_b)} + \frac{N_0}{2E_b\Omega}\right\}^{-1}, \tag{3.5.1}$$

where E_b represents the bit energy of the reference CU and Ω is the path strength. Parameter $q(L_p,\delta)$ in (3.5.1) is a function of the total number of paths received from the reference user, L_p, and the rate of exponential decay of multipath intensity profile (MIP), denoted by δ [15]. With proper scaling of the average transmit power of the reference CU in (3.4.3), it can be assumed that $\Omega = 1$. Given that the adaptive noise is zero-mean Gaussian process it can be shown that approximately $BER = Q(\sqrt{SNR})$, where $Q\ (\beta)\ \frac{1}{\sqrt{2\pi}}\int_0^\beta e^{-u^2/2}\,du$ [66]. Hence, in the adaptive transmission case, $E_b\Omega\ /N_0/2$ may be replaced by the outer loop optimum SNR-target, $\sigma(k,n;P_b)$, which in this section is set and adjusted based on the number of active primary and cognitive users. For this system the probability of instantaneous bit error rate as a function of the spreading factor can be determined by the following equation

$$BER = Q\left(\sqrt{\left\{\frac{q(L_p,\delta)-1}{2N(k,n;P_b)} + \frac{(k+n)q(L_p,\delta)}{3N(k,n;P_b)} + \frac{1}{\sigma(k,n;P_b)}\right\}^{-1}}\right). \tag{3.5.2}$$

Using the BER expression in (3.5.2), the approximation $Q(x) \le 0.5e^{-x^2/2}$ [82], and considering that the worst case scenario of BER is when it takes the maximum value of the target probability of bit error, $P_b = BER$, the deduction is

$$P_b = \frac{1}{2} \times \exp\left\{-\frac{1}{2}\left[\frac{q(L_p,\delta)-1}{2N(k,n;P_b)} + \frac{(k+n)q(L_p,\delta)}{3N(k,n;P_b)} + \frac{1}{\sigma(k,n;P_b)}\right]^{-1}\right\}. \tag{3.5.3}$$

Hence, the spreading factor for a matched-filter-based receiver is derived as:

$$N(k,n;P_b) = \frac{-\ln 2P_b \sigma(k,n;P_b)\,\Phi(k,n)}{6\ln 2P_b + 3\sigma(k,n;P_b)}, \tag{3.5.4}$$

where

$$\Phi(k,n) = \left[3\big(q(L_p,\delta)-1\big) + 2(k+n)q(L_p,\delta)\right]. \tag{3.5.5}$$

By replacing (3.5.4) into (3.4.6), the Lagrangian equation can be written as

$$L(\sigma(.,.),\varphi) = \frac{N_{chip}}{B}\sum_{n=1}^{n_{max}}\sum_{k=1}^{k_{max}} \frac{6\ln 2P_b + 3\sigma(k,n;P_b)}{-\ln 2P_b\sigma(k,n;P_b)\,\Phi(k,n)} r(n)h(k)$$

$$+\varphi\sum_{n=1}^{n_{max}}\sum_{k=1}^{k_{max}} \int_{g_{cp},\gamma_c} |g_{cp}|^2 \frac{\sigma(k,n;P_b)}{\gamma_c} r(n)h(k)f_G(g_{cp})f_\Gamma(\gamma_c)d\gamma_c dg_{cp} - \frac{Q_{\text{avg}}}{\bar{S}}. \tag{3.5.6}$$

The concavity condition of the above Lagrangian equation is proved in Appendix A. Taking derivative of $L(\sigma(.,.),\varphi)$ with respect to $\sigma(k,n;P_b)$ and setting the result equal to zero, the optimal outer loop SNR-target of the reference CU for the matched filter detector can be derived as

$$\sigma(k,n;P_b) = \sqrt{\frac{-6N_{chip}}{B\Phi(k,n)\varphi E[1/\gamma_c]E\left[|g_{cp}|^2\right]}}. \tag{3.5.7}$$

The above equation shows the optimal SNR-target as a function of the number of active primary and cognitive users, k and n, respectively, where φ depends on the distribution of k and n, $h(k)$ and $r(n)$, respectively. In cellular systems the number of active user in the cell is typically modelled by a Poisson random variable. Therefore, the pdf of k and n are respectively given by

$$h(k) = e^{-\lambda_p/\mu_p} \frac{\left(\lambda_p/\mu_p\right)^k}{k!}, \tag{3.5.8}$$

and

$$r(n) = e^{-\lambda_c/\mu_c} \frac{\left(\lambda_c/\mu_c\right)^n}{n!}, \tag{3.5.9}$$

where λ_p, is the rate of arrival of primary mobile users, λ_c is CUs' arrival rate, $1/\mu_p$, is the average service time for primary users and $1/\mu_c$ is CUs' average service time [10, 86]. Replacing (3.5.7), (3.5.8) and (3.5.9) into the average received-interference constraint in (3.4.5), the following inequality is found:

$$\sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} \int_{g_{cp},\gamma_c} \left|g_{cp}\right|^2 \frac{1}{\gamma_c} \sqrt{\frac{-6N_{chip}}{B\Phi(k,n)\varphi E[1/\gamma_c] E\left[\left|g_{cp}\right|^2\right]}} \times r(n)h(k) f_G\left(g_{cp}\right) f_\Gamma(\gamma_c) d\gamma_c dg_{cp} < \frac{Q_{\text{avg}}}{\bar{S}}. \tag{3.5.10}$$

Using the active constraint from (3.5.10), and the Kuhn-Tucker constraint qualification [83], the optimum value of the Lagrangian multiplier, φ is obtained as

$$\varphi = \frac{-6N_{chip}(\bar{S})^2}{B{Q_{\text{avg}}}^2} \zeta^2 e^{-2\left(\lambda_p/\mu_p + \lambda_c/\mu_c\right)} E[1/\gamma_c] E\left[\left|g_{cp}\right|^2\right], \tag{3.5.11}$$

where

$$\zeta = \sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} \frac{1}{\sqrt{\Phi(k,n)}} \frac{\left(\lambda_p/\mu_p\right)^k}{k!} \frac{\left(\lambda_c/\mu_c\right)^n}{n!}. \tag{3.5.12}$$

Subsequently, by replacing (3.5.4) into (3.4.2) and replacing the spreading factor with its optimal value (a function of number of active primary and cognitive users and BER-target), the average spectral efficiency can be computed as

$$\frac{R}{B} = \frac{-3N_{chip}}{B}\ e^{-\left(\lambda_p/\mu_p+\lambda_c/\mu_c\right)} \left(\frac{\Psi}{\ln 2P_b} + \frac{2\zeta^2 \bar{S} E[1/\gamma_c] E\left[\left|g_{cp}\right|^2\right]}{Q_{\text{avg}}} e^{-\left(\lambda_p/\mu_p+\lambda_c/\mu_c\right)} \right), \tag{3.5.13}$$

where

$$\Psi = \sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} \frac{1}{\Phi(k,n)} \frac{\left(\lambda_p/\mu_p\right)^k}{k!} \frac{\left(\lambda_c/\mu_c\right)^n}{n!}. \tag{3.5.14}$$

Equation (3.5.14) presents the reference CU average spectral efficiency when the total channel inversion policy is used, i.e. (3.3.5). For the case that truncated channel inversion (tci) policy is practiced, i.e. (3.3.6), the average spectral efficiency of the reference CU, can be evaluated as

$$\begin{aligned} \left(\frac{R}{B}\right)^{tci} &= \frac{-3N_{chip}}{B}\ p(\gamma_c > \gamma_{c-Th}) e^{-\left(\lambda_p/\mu_p+\lambda_c/\mu_c\right)} \\ &\times \left(\frac{\Psi}{\ln 2P_b} + \frac{2E[1/\,\gamma_c]_{\gamma_{c-Th}} E\left[\left|g_{cp}\right|^2\right] \zeta^2 \bar{S}}{Q_{\text{avg}}} e^{-\left(\lambda_p/\mu_p+\lambda_c/\mu_c\right)} \right), \end{aligned} \tag{3.5.15}$$

where

$$E[1/\gamma_c]_{\gamma_{c-Th}} = \int_{\gamma_{c-Th}} \frac{1}{\gamma_c} f_\Gamma(\gamma_c)\, d\gamma_c, \tag{3.5.16}$$

and $p(\gamma_c > \gamma_{c-Th})$ specifies the probability that the SNR is more than the threshold value, γ_{c-Th}. Therefore, $p(\gamma_c > \gamma_{c-Th})$ indicates the channel conditions under which transmission can be performed and the reference CU can operate. For truncated channel inversion, the SNR-target is determined by

$$\sigma_{opt}^{tci}(k,n;P_b) = \sqrt{\frac{-6N_{chip}}{B\Phi(k,n)\varphi^{tci}\, E[1/\gamma_c]_{\gamma_{c-Th}} E\left[\left|g_{cp}\right|^2\right]}}, \tag{3.5.17}$$

where

$$\varphi^{tci} = \frac{-6N_{chip}(\bar{S}\,)^2\, E[1/\gamma_c]_{\gamma_{c-Th}} E\left[\left|g_{cp}\right|^2\right] e^{-2\left(\lambda_p/\mu_p + \lambda_c/\mu_c\right)} \zeta^2}{B{Q_{\text{avg}}}^2}. \tag{3.5.18}$$

3.6 Peak and Average Received-Interference

This section investigates the maximum achievable average spectral efficiency of the reference CU under joint peak and average received-interference constraints at the receiver of the primary network. Similar to the scenario in Section 3.4, operation of the primary receiver necessitates that the average interference originated from the reference CU be kept below a pre-set limit. Also at the same time, the peak received-interference by the primary receiver should be limited as it does not tolerate interference higher than a certain threshold at any time during the transmission of the reference CU. The motivation of this analysis comes from the fact that there is also a peak interference limitation in practical communication systems, so that the primary users' QoS requirements are always guaranteed at any given time. Therefore, to avoid reducing the performance of the primary users at any instant, the peak received-interference imposed on the primary receivers as a result of the transmission performed by the reference CU is also limited.

Therefore, in this section, by using the same joint optimization technique as in section 3.5, the maximum average spectral efficiency of the reference CU subject to pre-defined limits on both average and peak received-interferences is assessed. Hence, denoting the average and peak received-interference values by Q_{avg} and Q_{peak}, respectively, the optimization problem can be written as:

$$\max_{\sigma(.,.)} \qquad \frac{R}{B} = \frac{N_{chip}}{B} \sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} \frac{1}{N(k,n;P_b)} r(n)h(k), \tag{3.6.1}$$

subject to:

$$\sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} \int_{g_{cp},\gamma_c} |g_{cp}|^2 \, S(\gamma_c,k,n) r(n) h(k) f_G(g_{cp}) f_\Gamma(\gamma_c) d\gamma_c dg_{cp} < \frac{Q_{\text{avg}}}{\bar{S}}, \tag{3.6.2}$$

and

$$|g_{cp}|^2 \, S(\gamma_c,k,n) \leq \mathrm{Q}_{\text{peak}}. \tag{3.6.3}$$

By using the same approach as in section 3.5, the above convex optimization problem is solved using Lagrangian method. The respective optimum SNR-target is calculated as

$$\sigma(k,n;P_b)=\begin{cases}\sqrt{\dfrac{-6N_{chip}}{B\Phi(k,n)\varphi E[1/\,\gamma_c]E\left[\left|g_{cp}\right|^2\right]}} & \dfrac{\left|g_{cp}\right|^2}{\gamma_c}\geq\dfrac{Q_{peak}}{\bar{S}},\\[2ex] \dfrac{\gamma_c Q_{peak}}{\left|g_{cp}\right|^2\bar{S}} & \dfrac{\left|g_{cp}\right|^2}{\gamma_c}\leq\dfrac{Q_{peak}}{\bar{S}}.\end{cases}$$

(3.6.4)

As can be seen from (3.6.4), the reference CU benefits from the weak link between its transmitter and the receiver of primary network and transmit at higher rate. However this transmission is limited by $\left(\gamma_c Q_{peak}\right)/\left(\left|g_{cp}\right|^2\bar{S}\right)$ to satisfy the peak received-interference constraint set by the primary network.

A practical fading model in wireless communications is Nakagami distribution which better fits a wide range of empirical data by adjusting a single fading parameter, m. In this case, γ_c is Gamma-distributed [57]:

$$p_\Gamma(\gamma_c)=\frac{1}{\Gamma(\mathrm{m})}\left(\frac{m}{E[\gamma_c]}\right)^m\gamma_c{}^{(m-1)}e^{\frac{-m\gamma_c}{E[\gamma_c]}}\quad\gamma_c\geq 0,$$

(3.6.5)

where $\Gamma(\alpha)$ is the Gamma function, given as $\Gamma(\alpha)=\int_0^\infty t^{\alpha-1}e^{-t}dt,\alpha>0$. Evoking that $\left|g_{cp}\right|^2$ is the channel power gain between the cognitive transmitter and the receiver of the primary network, (interference channel), the Interference power-to-Noise-Ratio (INR) can be defined as

$$\gamma_{cp}=\frac{\bar{S}\left|g_{cp}\right|^2}{N_0B}.$$

(3.6.6)

Both γ_{cp} and $\left|g_{cp}\right|^2$ are Gamma-distributed and the distribution of γ_{cp} is given by

$$p_{\Gamma}(\gamma_{cp}) = \frac{1}{\Gamma(\mathrm{m})}\left(\frac{m}{E[\gamma_{cp}]}\right)^{m} {\gamma_{cp}}^{(m-1)} e^{\frac{-m\gamma_{cp}}{E[\gamma_{cp}]}} \quad \gamma_{cp} \geq 0.$$

(3.6.7)

Now, let v denotes a random variable, where $v = \frac{|g_{cp}|^2}{\gamma_c}$. Then, by recalling that the distribution of the ratio between two Gamma distributed random variables with parameters α_1 and α_2 is a Beta prime distribution with parameters α_1 and α_2 [56],[18], the distribution of the random variable v for a case that both channels, g_c and g_{cp}, have the same Nakagami fading parameter, m can be found as

$$f_V(v) = \frac{v^{m-1}}{\beta(m,m)(v+1)^{2m}}$$

(3.6.8)

where $\beta(\alpha_1, \alpha_2)$ is the beta function defined as

$$\beta(\alpha_1, \alpha_2) = \frac{\Gamma(\alpha_1)\Gamma(\alpha_2)}{\Gamma(\alpha_1 + \alpha_2)}$$

(3.6.9)

Hence, the total average spectral efficiency of the reference CU from (3.6.4) and (3.6.8) can be calculated as:

$$\frac{R}{B} = \int_{0}^{\frac{Q_{peak}}{\bar{S}}} \left(\frac{R}{B}\right) \frac{v^{m-1}}{\beta(m,m)(v+1)^{2m}} dv + \int_{\frac{Q_{peak}}{\bar{S}}}^{\infty} \left(\frac{R}{B}\right) \frac{v^{m-1}}{\beta(m,m)(v+1)^{2m}} dv.$$

(3.6.10)

For general m, there is not a simple closed-form expression for average spectral efficiency, hence should be calculated numerically. However, for $m = 1$, Rayleigh fading, and for $m = 2$, exact closed form expressions can be obtained for the average spectral efficiency. By inserting the optimal value of $\sigma(k, n; P_b)$ in (3.6.10) closed form expressions can be found for the average spectral efficiency of the reference CU when joint optimization of rate control and outer loop power control technique is used under peak and average received-interference constraints and under Rayleigh fading channel conditions, as:

$$\frac{R}{B} = \frac{2\zeta^2 E[v]\bar{S}\varpi}{\chi Q_{\text{avg}}} \, e^{-(\lambda_p/\mu_p+\lambda_c/\mu_c)} + \frac{\Psi\varpi}{\ln 2P_b} + \frac{2\bar{S}\Psi\varpi}{Q_{peak}}\left(\ln(\chi) + \left(\frac{1}{\chi}\right) - 1\right), \tag{3.6.11}$$

where

$$\varpi = \frac{-3N_{chip}}{B} e^{-(\lambda_p/\mu_p+\lambda_c/\mu_c)}\,, \tag{3.6.12}$$

and

$$\chi = \left(\frac{Q_{peak}}{\bar{S}} + 1\right). \tag{3.6.13}$$

Also for a case that $m = 2$, after some manipulation the following closed form expression can be found for (3.6.10)

$$\frac{R}{B} = \frac{6\Psi\varpi}{\ln 2P_b} - \frac{12\zeta^2 E[v]\bar{S}\varpi}{\chi^2 Q_{\text{avg}}} e^{-(\lambda_p/\mu_p+\lambda_c/\mu_c)}\left(\frac{2-3\chi}{6\chi}\right) + \frac{12\bar{S}\Psi\varpi}{Q_{peak}}\left[\frac{1}{\chi}\left(-1+\frac{1}{\chi}-\frac{1}{3(\chi)^2}\right) + {}^{1}\!/_{3}\right]. \tag{3.6.14}$$

3.7 Variable Interference Temperature

In this section the aim is to derive an expression for the spectral efficiency of the reference CU where the acceptable value of the CUs' peak interference on the primary receiver is set dynamically as a function of the number of active users using the primary frequency spectrum:

$$Q_{peak} = Q_{peak}(k, n). \tag{3.7.1}$$

This assumption has a simple practical explanation. Since all the primary and cognitive users exploit the same spectral bandwidth, they interfere with each other. This intra-interference should be taken into account in setting of the acceptable peak interference on the licensed users. In static setting of the threshold two contradictory requirements should be considered. The first is to guarantee the SNR quality of the primary users as the licensed users, and the second is to maximize the throughput of the CUs. The former implies a very low peak interference temperature, i.e. setting the threshold conservatively, whereas the latter requires a high value of peak interference threshold, which can result in violation of QoS requirements of the licensed users at some instance of time.

A trade-off can be achieved by dynamically adapting the peak interference temperature to the number of all active users (primary plus cognitive) that exploit primary frequency band in such a way that the maximum possible throughput is provided to the CUs, whilst the quality of the primary users is guaranteed. Hence, the peak interference threshold should decrease with an increase in the number of active users in the primary network. From the CU's point of view, the base-station and radio network controller (RNC) routinely react to the number of active users in the primary network by changing the value of the peak interference limit. Consequently, the cognitive base-station sends commands to lower the transmission power as the licensed service gets more saturated. In other words, by listening to the power control commands, the reference CU is able to adjust its transmission power such that less interference is imposed on the primary users when the number of active users in the primary network increases.

Although allowing less transmit power to the CUs would not be desirable from the CU's perspective, but as it will be shown in the numerical results, the QoS of primary users will be guaranteed whilst the CUs' throughput is increased compared to static conservative threshold-setting. The respective optimization problem can be presented as follows

$$\max_{\sigma(.,.)} \quad \frac{R}{B} = \frac{N_{chip}}{N(k,n;P_b)B}, \tag{3.7.2}$$

subject to:

$$\int_{g_{cp},\gamma_s} g_{cp} \frac{\sigma(k,n;P_b)}{\gamma_c} f_G(g_{cp}) f_\Gamma(\gamma_c) d g_{cp}\, d\gamma_c \leq \frac{Q_{avg}}{\bar{S}}, \tag{3.7.3}$$

and

$$|g_{cp}|^2 \frac{\sigma(k,n;P_b)}{\gamma_c} \leq \frac{Q_{peak}(k,n)}{\bar{S}}. \tag{3.7.4}$$

Using Lagrangian optimization method, the maximum spectral efficiency of the reference CU is found as a function of the number of active users in the primary network. The corresponding maximum throughput under Nakagami fading conditions with $m = 2$, can be obtained as:

$$\frac{R}{B}(k,n) = \frac{6\Psi\varpi}{\ln 2P_b} - \frac{12\varpi\bar{S}E[v]\zeta^2}{Q_{\text{avg}}} e^{-(\lambda_p/\mu_p+\lambda_c/\mu_c)}\left(\frac{2-3\chi}{6\chi}\right)$$
$$-\frac{12\bar{S}\Psi\varpi}{Q_{peak}(k,n)}\left[\frac{1}{\chi}\left(-1+\frac{1}{\chi}-\frac{1}{3(\chi)^2}\right)-{}^{1}/_{3}\right],$$

(3.7.5)

where

$$\chi = \left(\frac{Q_{peak}(k,n)}{\bar{S}}+1\right).$$

(3.7.6)

3.8 Performance Results

This section numerically illustrates the performance of the shared-spectrum joint-optimization method and examines its advantages and limitations compared to the variable spreading factor system which does not make use of the optimum out loop SNR-target. Both flat fading ($L_p = 1$) and multipath fading ($L_p \geq 1$) conditions are examined in this section. The system that does not exploit SNR-target in the outer loop would not select the best spreading factor in terms of average spectral efficiency maximization and hereafter referred to as non-optimized system. Hence, it is assumed in the non-optimized system the SNR-target is kept constant and is equal to $\bar{S}/\left(Q_{\text{avg}}E\left[\left|g_{cp}\right|^2\right]E[1/\gamma_c]\right)$. A continues-rate spreading factor adaptation has been considered. Therefore, results serve as upper bounds for the achievable throughput of CUs. In the numerical results, maximum number of the primary users is set to $k_{max} = 70$, maximum number of the CUs seeking the opportunity to exploit the primary frequency band is set to $n_{max} = 15$, channel bandwidth is $B = 5$ MHz, and chip rate is $N_{chip} = 3.84$ Mcps. Also it is assumed that $\bar{S} = 0.25$ Watt and $N_0 = -174$ dBm/Hz.

In the inner loop, transmit power is adapted to γ_c through the total or truncated channel inversion policies. For the case of channel inversion policy and with ≥ 2 :

$$E[1/\,\gamma_c] = \frac{m}{(m-1)E[\gamma_c]}\,.$$

(3.8.1)

Also when the truncated channel inversion policy is used in the inner loop, $E[1/\,\gamma_c]$ is replaced with $E[1/\,\gamma_c]_{\gamma_{c-Th}}$:

$$E[1/\,\gamma_c]_{\gamma_{c-Th}} = \frac{m\Gamma\left(\mathrm{m}-1, \frac{m\gamma_{c-Th}}{E[\gamma_c]}\right)}{E[\gamma_c](m-1)!}\,,$$

(3.8.2)

where $\Gamma(\alpha, \beta)$ is defined as $\Gamma(\alpha, \beta) = \int_{\beta}^{\infty} t^{\alpha-1}e^{-t}dt, \alpha > 0$ [1].

Furthermore, when truncated channel inversion is in use, $p(\gamma_c > \gamma_{c-Th})$, is computed by

$$p(\,\gamma_c > \gamma_{c-Th}) = \frac{m\Gamma\left(m, \frac{m\gamma_{\gamma_{c-Th}}}{E[\gamma_c]}\right)}{(m-1)!},$$

(3.8.3)

which, for $m = 1$, is equal to $e^{\gamma_{c-Th}/\,E[\gamma_c]}$. Therefore, the outage probability under Rayleigh fading is calculated by

$$p(\gamma_c > \gamma_{c-Th}) = 1 - e^{\gamma_{c-Th}/E[\gamma_c]}.$$

(3.8.4)

In the proposed shared-spectrum system, the cognitive (secondary) network is saturated and the QoS of its users may be reduced by offering service to the new users, so the cognitive base station seeks permission from the adjacent cell's base station (primary network) to allow the CUs to exploit its frequency band during the busy time period. Therefore, the under-utilized part of the primary spectrum is shared with the cognitive network and utilized by the CUs.

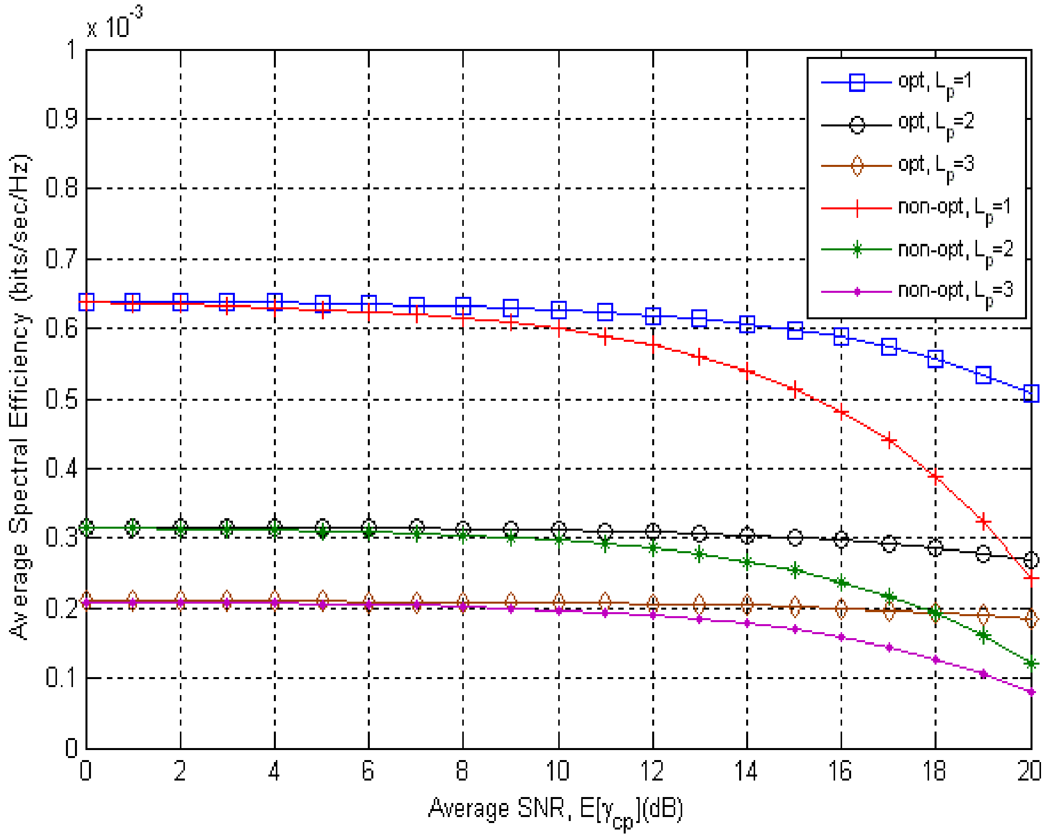

Figure 3.2: Average spectral efficiency of the reference CU for various INR values, for different number of paths; $\lambda_p = 0.50$, $\mu_p = 0.006$, $\lambda_c = 0.12$, $\mu_c = 0.018$, $m = 2$, $P_b = 10^{-4}$, $\delta = 0$, Q_{avg}=$10N_0B$, $E[\gamma_c] = 25dB$.

In Fig. 3.2 the impact of the INR on the maximum average spectral efficiency of the reference CU is studied, and the figure plots the average spectral efficiency versus $E[\gamma_{cp}]$ for different number of paths. The figure shows that, the average spectral efficiency decreases sharply by increasing the interference caused by the activity of the reference CU. The reason for such a severe decline is that the primary network limits the access of the reference CU to the primary resources by applying the constraint on the average received-interference caused by its operation. As illustrated by Fig. 3.2, the proposed optimization scheme provides a significant improvement in the average spectral efficiency, particularly in the higher average $E[\gamma_{cp}]$ region. The plausible explanation for the attained enhancement is that in the proposed scheme the SNR-target is set to its optimal value according to the channel conditions by the outer loop power control. Then, for achieving such SNR-target the transmission rate of the reference CU is adapted to the channel condition by using the optimum variable spreading factor. On the other hand, the non-optimized system is using the non-optimal SNR-target that can result in a waste of system resources. In addition, increasing the number of paths lowers the achievable average spectral efficiency as larger variable spreading factors would be required.

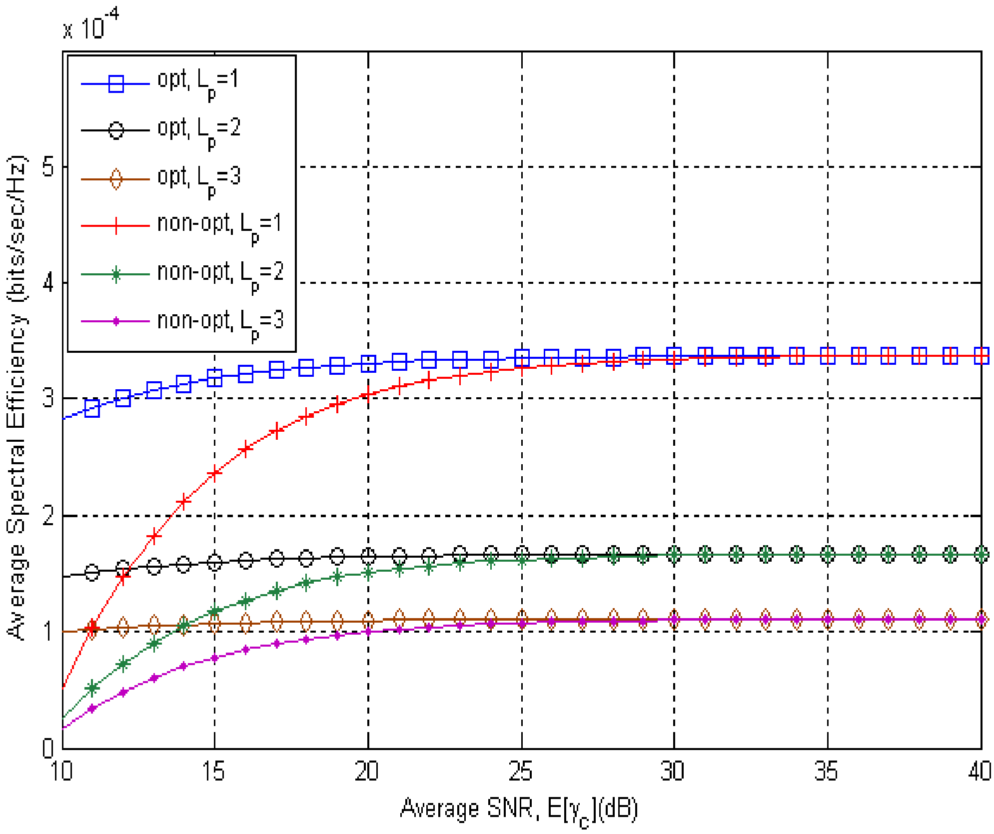

Figure 3.3: Average spectral efficiency of the reference CU for the different number of paths; $\lambda_p = 0.50$, $\mu_p = 0.006$, $\lambda_c = 0.12$, $\mu_c = 0.018$, $m = 2$, $P_b = 10^{-4}$, $\delta = 0$, Q_{avg}=$10N_0B$, $E[\gamma_{cp}] = 10dB$.

Fig. 3.4 plots average spectral efficiency for various BER-targets, P_b, values when $L_p = 2$. Two points can be clearly observed. First is the improvement attained by using the joint-optimization scheme specifically for lower values of $E[\gamma_c]$. The second is that using tighter values for BER-target will result in lower average spectral efficiency. This occurs because with higher BER-target values the outage condition is limited and thus the average transmission rate over all channel conditions improves. For instance, a nearly 59% rise in bits/s/Hz is attainable at $E[\gamma_c] = 30dB$ by changing the target BER from 10^{-3} to 10^{-2}.

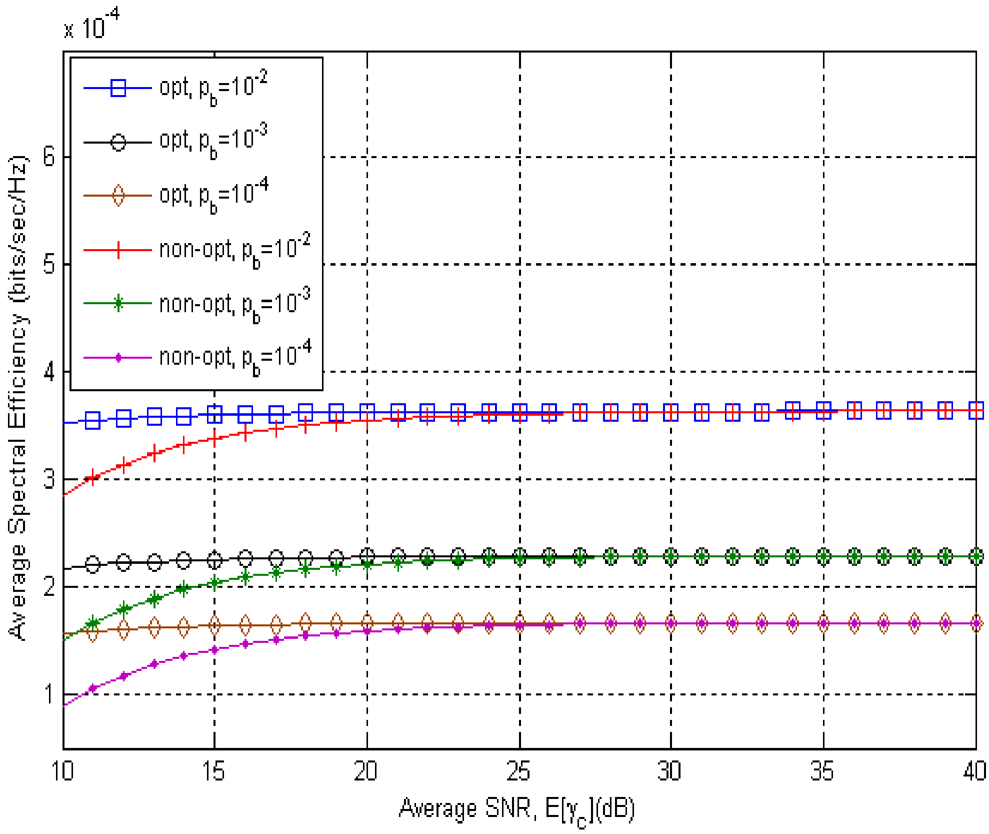

Figure 3.4: Average spectral efficiency of the reference CU for various BER-targets scenarios; $L_p = 2$, $\lambda_p = 0.50$, $\mu_p = 0.006$, $\lambda_c = 0.18$, $\mu_c = 0.012$, $m = 4$, $\delta = 0$, Q_{avg}=$10N_0B$, $E[\gamma_{cp}] = 10dB$.

In Fig. 3.5 the optimal and non-optimal average spectral efficiency values are displayed for different levels of the acceptable average received-interference threshold, Q_{avg}, for the truncated channel inversion policy. It is observable that a higher average received-interference limit (looser QoS constraint) results in larger average spectral efficiency. This would be expected, as a higher average spectral efficiency can be achieved when the primary receiver can tolerate more interference from the reference CU. It is also shown that the achievable gain that can be attained by using the proposed optimization scheme is considerably more when the lower threshold level is set for Q_{avg}.

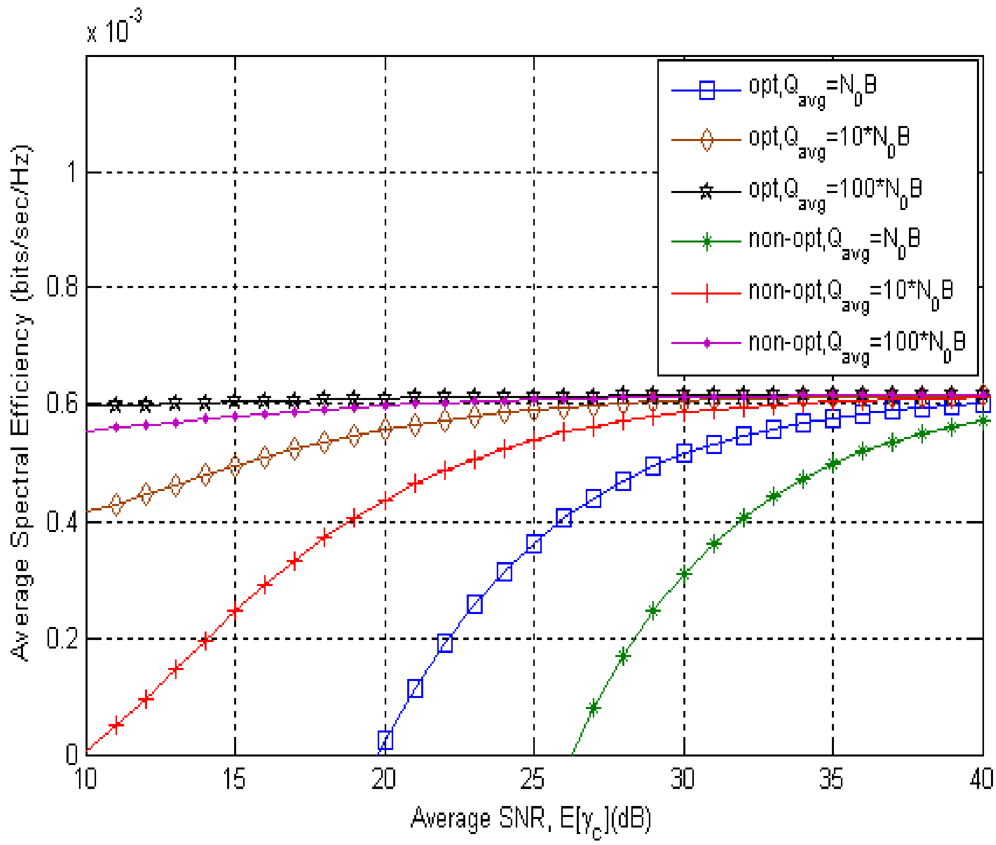

Figure 3.5: Comparison of optimized average spectral efficiency with non-optimized average spectral efficiency for different Q values; $L_p = 1,\ \lambda_p = 0.50$, $\mu_p = 0.006$, $\lambda_c = 0.12$, $\mu_c = 0.014,\ m = 1,\ \delta = 0,\ \gamma_0 = 3\text{dB},\ P_b = 10^{-4},\ E[\gamma_{cp}] = 10dB$.

Fig. 3.6 illustrates the alteration of the average spectral efficiency with increasing traffic load of both the primary and cognitive users, λ_p/μ_p and λ_c/μ_c, respectively, for the optimized scheme. As the number of active primary and cognitive users increases, average spectral efficiency decreases. The principal reason is higher MAI in the primary network that forces reduction in transmission rate of the reference CU with the aim of satisfying primary users' QoS constraint. It can also be seen that by raising $E[\gamma_c]$, average spectral efficiency rises as well. Predictably, increasing the number of paths would reduce the average spectral efficiency.

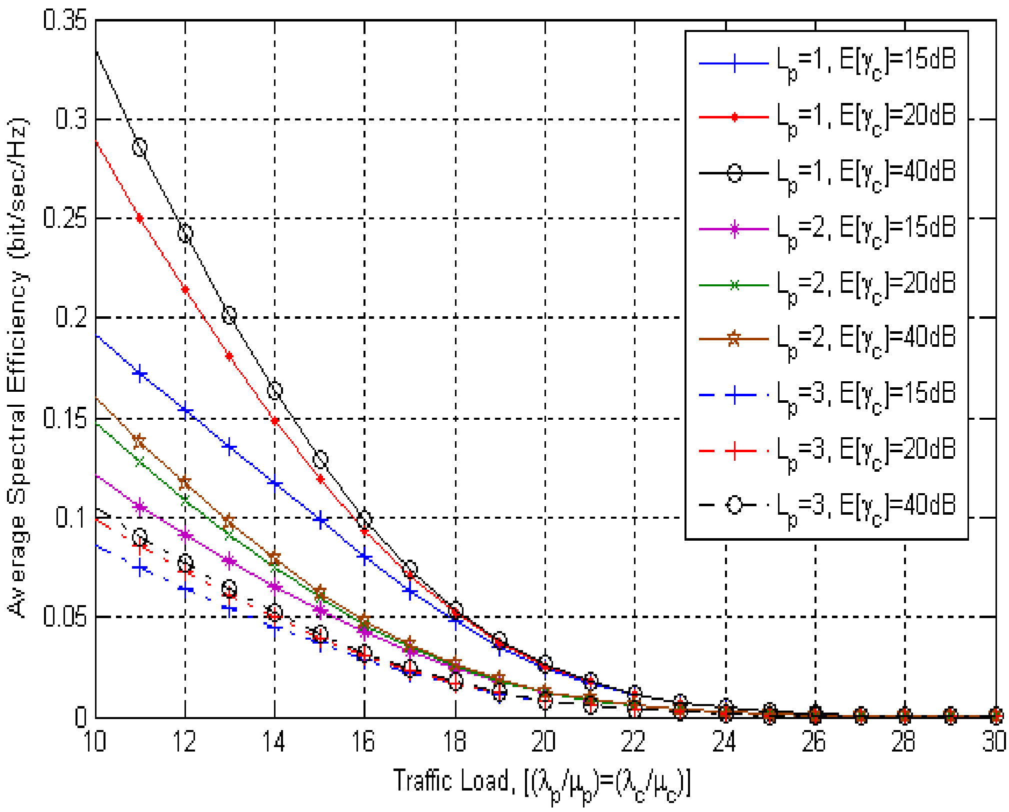

Figure 3.6: Average spectral efficiency of optimized scheme for range of primary and cognitive network traffic load, $\lambda_p/\mu_p = \lambda_c/\mu_c$ and different number of paths; $m = 2$, $P_b = 10^{-4}$, $\delta = 0$, Q_{avg}=$100N_0B$, $E[\gamma_{cp}] = 10dB$.

Fig. 3.7 demonstrates the achievable average spectral efficiency versus the average received-interference threshold, Q_{avg}, for the optimized system. From Fig. 3.7 it is evident that although imposing more relaxed Q_{avg} yields higher average spectral efficiency values but it also increases the possibility of violating the primary users' QoS requirements. Apart from the considerable gain that can be achieved by increasing the reference CU's SNR, it can be seen that for a given received average power, $E[\gamma_c]$, increasing the number of paths can significantly reduce the performance of the reference CU. The figure also shows that the average spectral efficiency significantly increases by employing the proposed joint optimization scheme especially in the lower average received-interference threshold region.

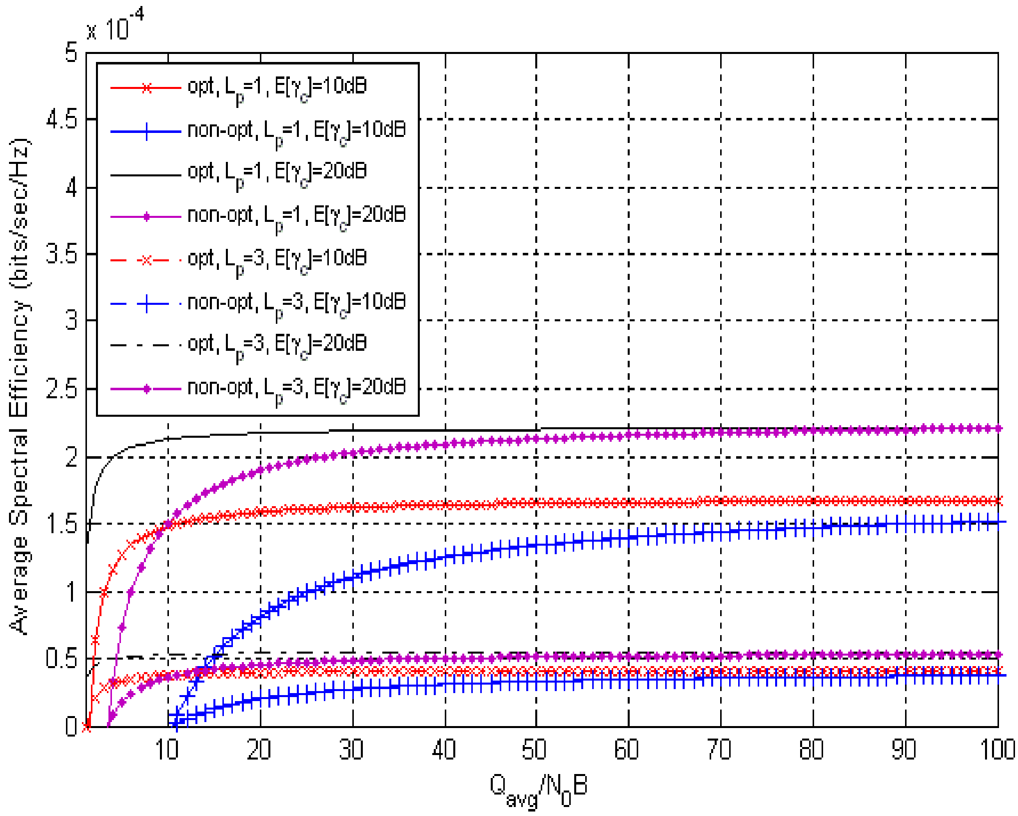

Figure 3.7: Average spectral efficiency of the optimized scheme for different values of Q and various numbers of paths; $\lambda_p = 0.525$, $\mu_p = 0.006$, $\lambda_c = 0.12$, $\mu_c = 0.014$, $m = 1$, $\delta = 0$, $P_b = 10^{-4}$, $\gamma_0 = 3\mathrm{dB}$, $E[\gamma_{cp}] = 10dB$.

Fig. 3.8 presents the plots for the average spectral efficiency under truncated channel inversion policy with peak and average received-interference constraints for different number of paths. In particular, the average spectral efficiency of the proposed optimized scheme is studied for various SNR levels of the reference CU and for different values of $\rho = \frac{Q_{\text{peak}}}{Q_{\text{avg}}}$.

For having a viable comparison with the previous scenario that only a constraint on the average received-interference is assumed, $E[\gamma_{cp}]$ is kept constant and the maximum average spectral efficiency is plotted versus $E[\gamma_c]$. Also, for comparison purpose, a result for the case where the average received-interference constraint is considered is also provided. Fig. 3.8 shows that, as ρ increases the average spectral efficiency curves converge towards the case with no peak constraint. The reason is that under the less restricted Q_{peak} threshold setting, the reference CU can transmit with higher power and as a result higher average spectral efficiency can be achieved. However, also it should be considered that applying a less restricted Q_{peak} threshold could also result in more chance of degrading the performance of the primary users.

Fig. 3.9 demonstrates an example of the scenario of section 3.7 with adaptive threshold setting. It illustrates the ratio of the reference CU transmitter interference to the reference primary receiver for different values of the number of active users in the primary network. In the adaptive-Q_{peak} scheme, $Q_{peak}(k,n)$, defines the maximum allowed interference on the reference primary receiver and it is considered as a staircase function. The width of each interval is given by $\frac{(k+n)}{l}$ where l is the range of users associated to the same threshold. The value of l is set to 5, and for each interval a constant threshold is set.

As can be seen, the interference threshold is lowered as the number of active user's increases. As demonstrated in Fig. 3.9, in the adaptive-Q_{peak} scheme the $Q_{peak}(k,n)$ decreases as the number of active users in the primary network increases. Hence, it provides an opportunity for the reference CU to achieve a higher average spectral efficiency when lower numbers of users exploit the primary spectrum compared to the case that the threshold value is set statically. On the other hand, by setting the tolerable peak received-interference value as a function of active users, the QoS of primary users can be guaranteed at all time. This can be successfully achieved by changing the threshold value to the lowest possible value, $Q_{peak}(k,n) = Q_{avg}$, and not allowing it to degrade the signal quality of the primary users during the busy period.

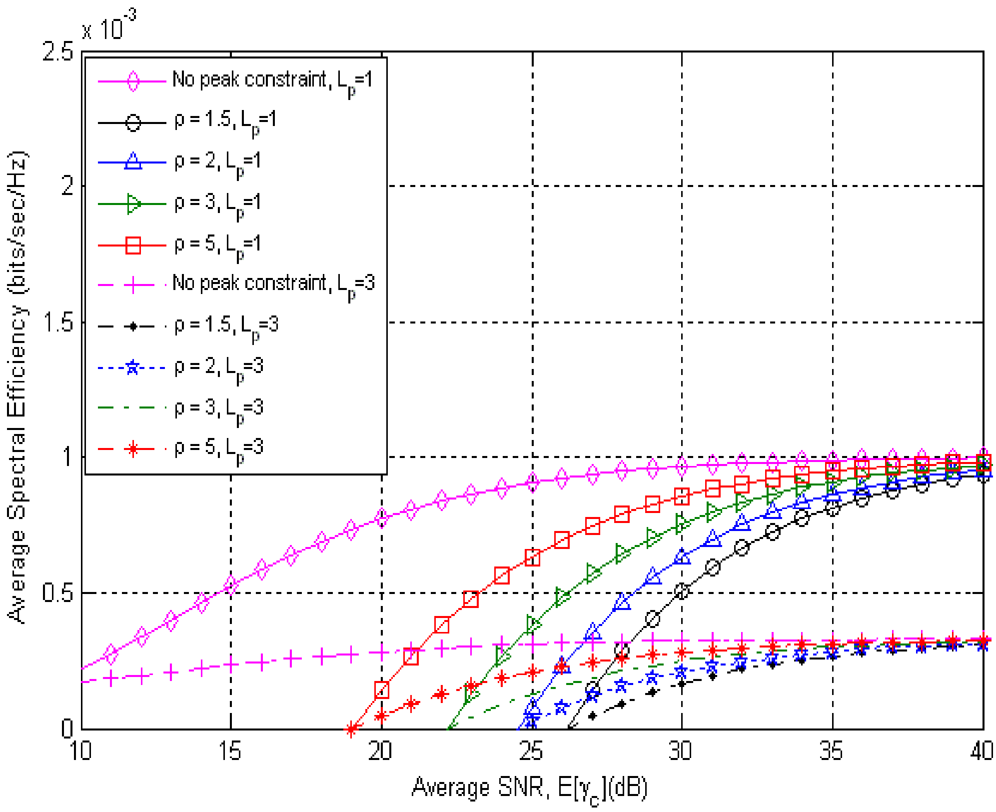

Figure 3.8: Average spectral efficiency of the reference CU under the peak and the average received-interference constraints for different number of paths and different values of $\rho = Q_{\text{peak}}/Q_{\text{avg}}$; $\lambda_p = 0.44$, $\mu_p = 0.006$, $\lambda_c = 0.12$, $\mu_c = 0.014$, $m = 1$, $\gamma_0 = 3\text{dB}$, $\delta = 0$, Q_{avg}=$10N_0B$, $P_b = 10^{-4}$, $E[\gamma_{cp}] = 10dB$,

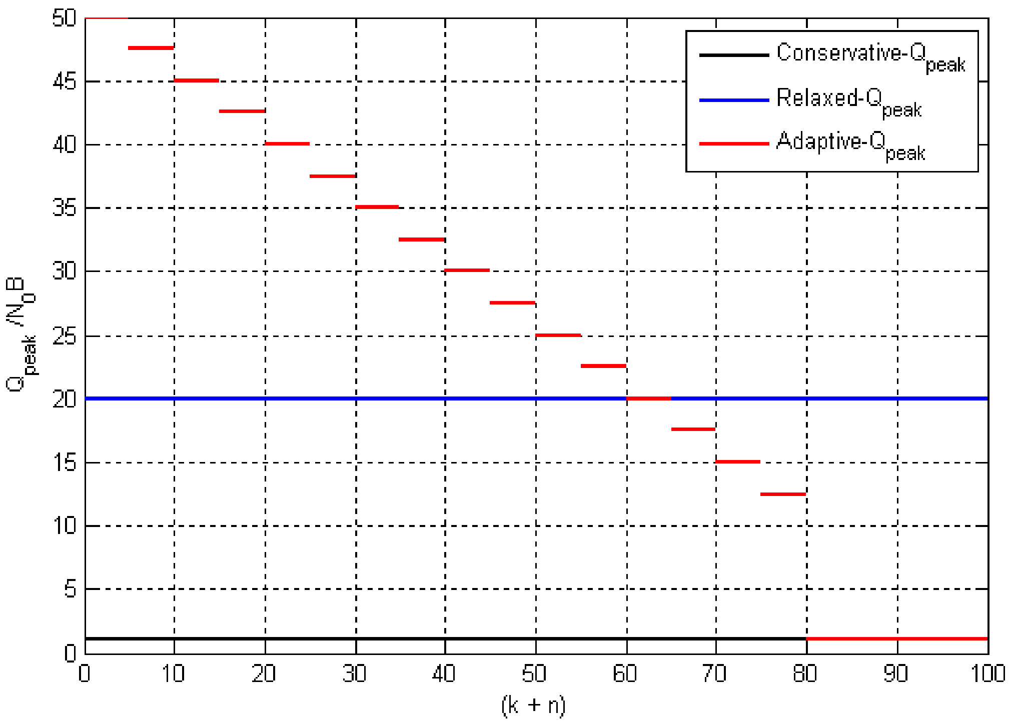

Figure 3.9: Maximum peak received-interference threshold value of the reference CU versus maximum number of active user in the primary network.

Fig. 3.10 presents the average spectral efficiency of the reference CU for various settings of the peak received-interference threshold and different number of paths. This confirms that a considerable gain can be achieved by setting the Q_{peak} dynamically according to the number of active users in the primary network comparing to the scenario when the Q_{peak} is set conservatively. Two static threshold scenarios are considered along with the proposed adaptive threshold scheme based on settings of Fig. 3.9. It is assumed that 20% of the active users in the primary network are the CUs and the rest are the primary users. Due to limitation of the maximum allowed transmit power in the adaptive-Q_{peak} scenario, higher average spectral efficiency, can be attained with the Relaxed-Q_{peak} compared to the adaptive-Q_{peak} at the expense of increasing the chance of violating the primary users' QoS. By adapting the maximum allowed interference limit the amount of interference that the reference CU may impose on the primary network decreases by increasing the number of active users. Although the primary users' QoS requirements can be always assured by using the Conservative-Q_{peak}, however the reference CU's average spectral efficiency would be severely degraded. A trade-off can be attained between the primary users' QoS and the cognitive users' average spectral efficiency by using the proposed adaptive-Q_{peak} scheme. Therefore, in brief, although average spectral efficiency in the adaptive-Q_{peak} scheme may be lower compared to the Relaxed-Q_{peak} case, but adaptive-Q_{peak} scheme can assure that QoS of the primary service is always guaranteed at each interval and simultaneously result in a better average spectral efficiency for the CU compared to the conservative setting scenario. This can be seen by comparing the adaptive-Q_{peak} curves with those corresponding to Conservative-Q_{peak}.

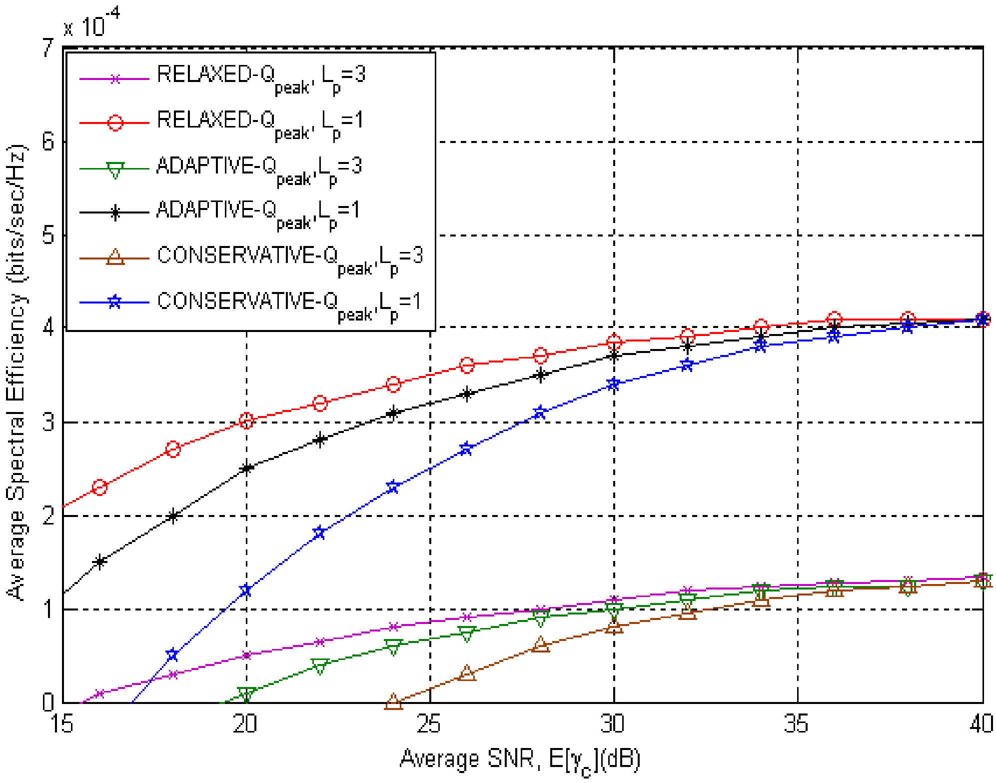

Figure 3.10: Average spectral efficiency for adaptive and non-adaptive maximum tolerable interference scenarios for different number of paths; $\lambda_p = 0.50$, $\mu_p = 0.006$, $\lambda_c = 0.12$, $\mu_c = 0.014$, $m = 2$, $\delta = 0$, $P_b = 10^{-4}$, $E[\gamma_{cp}] = 10dB$, $Q_{\text{avg}}=10N_0B$.

3.9 Summary

A shared-spectrum system is considered and the spectral efficiency of the reference CU under joint optimization of the outer loop SNR-target and variable spreading factor with constraints on the peak and the average received-interference on the primary receiver is assessed. The scheme was analyzed for a frequency-selective channel with MRC coherent RAKE receiver. It was shown that for lower SNR values the proposed scheme attained a considerable gain compared to the non-optimized SNR-target case. In addition, heavy traffic loads can hugely reduce system performance and average spectral efficiency falls sharply as traffic load increases. Furthermore, the average spectral efficiency of the reference CU was determined under the joint peak and average receiver-interference constraints. Numerical results shows that although applying the peak constraint on top of the average received-interference constraint may reduce the performance of the reference CU but it can guarantee that the quality of primary signals is not degraded at any time. The case is also investigated where the maximum acceptable peak received-interference caused by the performance of the reference CU on the licensed users is dynamically set, based on the number of active users in the primary network. It was shown that this scheme is a useful trade-off between QoS of the primary service and the CU's throughput. In particular, the proposed scheme introduced a significant gain in system throughput at lower SNRs by using the joint-optimization of outer loop control, rate control and variable interference temperature in the spectrum sharing wireless systems.

Chapter 4

4. Impact of Primary Users Activity on the CUs' Average Spectral Efficiency

4.1 Contributions

At this point, the contributions of this chapter are summarized. This chapter will develop:

- Maximum total average spectral efficiency of the reference CU that uses the AB-OSA technique for utilizing the primary spectrum.
- An evaluation of the achievable gain in the CUs' throughput, which is attained by using the CR technology.
- A comparison between non-shared-spectrum ($P_I = 0$) and shared-spectrum ($P_I = 1$) systems.
- An evaluation of the impact of the primary network on the reference CU's throughput.
- A comparison between systems that use a non-optimal SNR-target and the system that uses the proposed joint optimization scheme.

In parallel, under total channel inversion power adaptation policy, this chapter derived:

- A closed-form solution for the optimal SNR-target (for both cognitive and primary networks), using the matched-filter detector.

- The optimal spreading factor for transmission for both networks, using the matched-filter detector.

4.2 Introduction

In Chapter 3, an algorithm is proposed for maximizing the CUs' throughput when the primary spectrum is being used concurrently by both primary and cognitive networks. Another most common access technique in CR networks is AB-OSA. In this access method, the primary network does not accept any inference from the CUs, therefore, the CUs are only allowed to conduct transmission in the circumstances in which the primary spectrum is not being used by the primary users. In this chapter the performance of the novel joint optimization technique that proposed in Chapter 3 is further analyzed for the scenario that the CUs are using the AB-OSA technique for utilizing the shared primary spectrum.

It is assumed that the cognitive network is monitoring the primary spectrum and exploits the primary frequency band when the number of active primary users is below the pre-set threshold; the primary spectrum is under-utilized. The CUs are using the cognitive network resources for transmitting data for a period of time that the activity of the primary network is higher than pre-defined limit. In this chapter, the spectrum is called *idle* in the period of time that the primary spectrum is under-utilized and for a fraction of time during which the number of active primary users is more than the pre-set limit, the licensed primary spectrum is referred to as *busy*. The CUs can utilize the cognitive spectrum subject to average transmit power and BER constraints set by the cognitive network. Likewise, the CUs exploit the primary bandwidth, when it is idle, subject to average transmit power and BER limits set by the primary network. The aim is to maximize the total throughput of the CUs subject to aforementioned constraints. Another goal is to evaluate the gain that the CUs can achieve by being able to share the licensed primary spectrum with the primary users. Specifically, this chapter numerically illustrates the achievable gain in CU's throughputs which is attained by employing the CR technology.

Same as the previous chapter, the average spectral efficiency is calculated for a reference CU. In the proposed CR system, the outer loop SNR-target and transmission rate of the reference CU are adapted to BER where total channel inversion policy is exploited for the inner-loop power control. Such an adaptation is done with respect to the number of active primary users for a certain period of time that the primary spectrum is available to the reference CU. Likewise, outer loop SNR-target is found based on the number of active CUs when the primary licensed frequency band is busy and the reference CU is utilizing the cognitive service frequency band. Moreover, the impact of the primary network's activity on the reference CU's spectral efficiency is investigated and it is highlighted that lower level of activity in the primary network results in higher gain in the reference CU's throughput. The performance of the proposed joint-optimization scheme is analyzed over Nakagami-m frequency-selective fading channels with conventional matched-filter detection, for the total channel inversion policy in the inner loop.

The reminder of this chapter is organized as follows: Section 4.3 presents system and channel models and parameters used throughout the chapter. Section 4.4 explains the spectrum sensing algorithm used in this work. Section 4.5 provides the formulation of average spectral efficiency of the reference CU optimization problem. Section 4.6 covers the derivation of the average spectral efficiency of the reference CU subject to specified constraints. Finally, the chapter is concluded in section 4.7.

4.3 System Overview

Suppose $n(t)$, $1 \leq n(t) \leq n_{max}$, is the number of active CUs, utilize the frequency band allocated to the cognitive network at any given time, t, where n_{max} is the maximum number of the CUs allowed to transmit data. It is worth to mention that, unlike the previous chapter that the CUs' term was referred to the cognitive users that utilize the primary frequency band, in this chapter the term CUs is referred to all the active cognitive users in the cognitive network. It is also assumed that $k(t)$, $1 \leq k(t) \leq k_{max}$, is the number of primary mobile users at time t where k_{max} is the maximum number of primary users permitted to communicate data at any given moment. Fig.4.1 shows the schematic diagram of the shared-spectrum system, for a fraction of time that the reference CU is permitted to utilize the idle primary frequency band. Both primary and cognitive users are transmitting data in the reverse link of the multiuser DS-CDMA cellular radio system. The aim here is to drive the average spectral efficiency of the reference CU and only the active primary users are regarded as MAI when primary frequency band is being used by reference CU for transmission. Similarly for a fraction of time that the reference CU exploits cognitive spectrum, only the other CUs are considered as MAI. BPSK modulation is used and the modulated data is transmitted to the base station of cognitive network over a frequency-selective fading channel.

The signal of the reference CU is spread over a bandwidth B by spreading factor, $N_{c,f_p}\left(k; BER_{c,f_p}^{t}\right)$, when the primary frequency band is being used by the reference CU where BER_{c,f_p}^{t} indicates the target bit error rate probability for the primary network. Also, the reference CU signal is spread over bandwidth B by spreading factor $N_{c,f_c}(n; BER_{c,f_c}^{t})$, when the frequency band belongs to the cognitive service is being exploited, where BER_{c,f_c}^{t} is the target bit error rate probability for the CUs. During the transmission zero-mean AWGN, $\tilde{n}(\mathrm{t})$, with a two-sided power spectral density of $N_0/2$ is added to the signal.

It is assumed for a fraction of time that the reference CU uses the primary frequency band, the frequency-selective channels between the reference CU transmitter and the cognitive receiver and channel between the reference CU transmitter and the primary receiver are $g_{cj,f_p}(t)$ and $g_{cpj,f_p}(t)$, respectively, with L_p paths, where $j = 1,..,L_p$ at time t. Channel gains between the reference CU transmitter and the cognitive receivers when data is transmitted over cognitive frequency band over j-th path is denoted as $g_{cj,f_c}(t)$, where $j = 1,..,L_p$. The knowledge of $g_{cj,f_p}(t)$ and $g_{cj,f_c}(t)$ is assumed to be available at the cognitive transmitter through CSI.

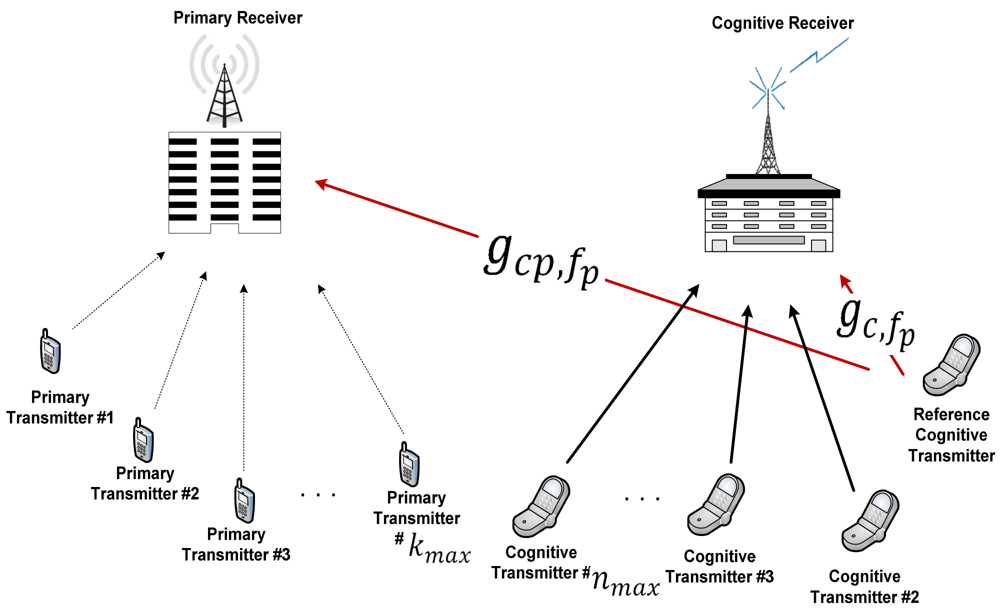

Figure 4.1: System model.

The instantaneous received SNR of the reference CU at the output of the MRC combiner of the cognitive receiver when the primary frequency band is used for communication is set by

$$\gamma_{c,f_p}(t) = \frac{\bar{S}_{\,c,f_p} \sum_{j=1}^{L_p} \left| g_{cj,f_p}(t) \right|^2}{N_0 B},$$

(4.3.1)

where $\bar{S}_{\,c,f_p}$ denotes the average transmit signal power of the reference CU when the primary spectrum is used for transmission.

Also the received SNR of the reference CU when it exploits the cognitive network spectrum is given by

$$\gamma_{c,f_c}(t) = \frac{\bar{S}_{\,c,f_c} \sum_{j=1}^{L_p} \left| g_{cj,f_c}(t) \right|^2}{N_0 B},$$

(4.3.2)

where $\bar{S}_{c,f_c}$ denotes the average transmit power of the reference CU when data is transmitted over the cognitive network spectrum.

The notion of time t is omitted in the rest of this chapter because $\gamma_{c,f_p}(t)$ and $\gamma_{c,f_c}(t)$ are assumed to be stationary. The aim is to set the SNR-target, using the outer loop power control, appropriated to the number of active primary and cognitive users and the target probability of bit error rate to its optimal value. For instance when the reference CU is transmitting data over the primary frequency band, SNR-target, $\sigma_{c,f_p}\left(k; BER^t_{c,f_p}\right)$, is set based on the number of active primary users and BER^t_{c,f_p}. Subsequently, adapted spreading factor is chosen in the inner loop in order to attain SNR-target, consequently this provides maximal spectral efficiency for the system. Same is done when the reference CU is using the cognitive network resources for transmitting data, and its SNR-target, $\sigma_{c,f_c}\left(n; BER^t_{c,f_c}\right)$, is set with respect to the number of active CUs and BER^t_{c,f_c}. Transmit power, $S_{c,f_p}\left(\gamma_{c,f_p}, k\right)$, adapted to number of active primary users in the primary service and the received SNR, in the inner loop with the intention of achieving $\sigma_{c,f_p}\left(k; BER^t_{c,f_p}\right)$, through the total channel inversion policy

$$\frac{S_{c,f_p}\left(\gamma_{c,f_p}, k\right)}{\bar{S}_{c,f_p}} = \frac{\sigma_{c,f_p}\left(k; BER^t_{c,f_p}\right)}{\gamma_{c,f_p}}, \tag{4.3.3}$$

Also when the cognitive frequency band is used for transmission, transmit power, $S_{c,f_c}\left(\gamma_{c,f_c}, n\right)$, adapted to the number of active CUs and the total channel inversion policy is defined by

$$\frac{S_{c,f_c}\left(\gamma_{c,f_c}, n\right)}{\bar{S}_{c,f_c}} = \frac{\sigma_{c,f_c}\left(n; BER^t_{c,f_c}\right)}{\gamma_{c,f_c}}, \tag{4.3.4}$$

4.4 Spectrum Sensing

The reference CU is seeking for an opportunity to utilize the frequency band licensed to the primary users. However, the reference CU is only allowed to transmit data over the shared-spectrum when the number of active users in the primary network is below the pre-set threshold, k_{limit}. Consequently, the reference CU should perform channel estimation that can be carried out through spectrum sensing for accessing the under-utilized part of the wireless frequency band. It is assumed that the spectrum sensing mechanism is perfect and the probabilities of miss-detection and false-alarm are zero. The received signal $y(t)$ at the reference CU receiver is given by

$$y(t) = \varphi p_p(t) + \tilde{n}(\mathrm{t}), \tag{4.4.1}$$

where φ represents the status of the primary network with respect to k_{limit}, $p_p(t)$ denotes the received licensed signal and $\tilde{n}(\mathrm{t})$ indicates the additive noise at the receiver side of the channel which is used by the reference CU for spectrum sensing respectively. Two possible conditions considered for φ can be written as, φ =1, when the number of users that exploit the primary frequency band is more than the pre-defined limit, the primary frequency band is busy, and φ =0 for otherwise.

The detection of the status of the primary network with respect to k_{limit}, can be formulated as a binary hypothesis testing problem

$$\begin{cases} \mathcal{H}_{p0}: & \varphi = 0, \\ \mathcal{H}_{p1}: & \varphi = 1, \end{cases} \tag{4.4.2}$$

where $\mathcal{H}_{p0}$ and $\mathcal{H}_{p1}$ represent the hypotheses corresponding to the primary spectrum being idle or busy, respectively. A spectrum sensing technique is employed by the reference CU to observe the received signal and decide on the two hypotheses, $\mathcal{H}_{p0}$ and $\mathcal{H}_{p1}$.

In the cooperative spectrum sensing method, all the CUs send the gathered sensing information to the combining user (Fusion) and it decides if the monitored channel can be utilized or not. Local information of the licensed primary channel availability attained by CUs is sent to the combining user through the dedicated control channel. In this work t is assumed that the reference CU only collects and combines the sensing information from the nearby cognitive users. Let Ω_{T_c} represents the sensing information about the primary channel collected by the reference CU transmitter and Ω_{R_c} indicates sensing information collected by the reference CU receiver. According to the Bayesian theorem, the conditional probability that the primary network spectrum being idle, P_I, is given by [94]

$$P_I = P(\mathcal{H}_{p0}|\Omega_{R_c}) = \frac{P(\Omega_{R_c}|\mathcal{H}_{p0}) * P(\mathcal{H}_{p0})}{P(\Omega_{R_c}|\mathcal{H}_{p1}) * P(\mathcal{H}_{p1}) + P(\Omega_{R_c}|\mathcal{H}_{p0}) * P(\mathcal{H}_{p0})}, \tag{4.4.3}$$

where $P(\mathcal{H}_{p0})$ and $P(\mathcal{H}_{p1})$ are the stable probabilities that the primary spectrum is idle or busy, respectively; $P(\Omega_{R_c}|\mathcal{H}_{p0})$ and $P(\Omega_{R_c}|\mathcal{H}_{p1})$ are the conditional probabilities that the sensing information, Ω_{R_c}, is given when the primary spectrum signal is idle or busy, respectively.

Furthermore, the conditional probability given that the primary spectrum being busy, P_B, is set by

$$P_B = P(\mathcal{H}_{p1}|\Omega_{T_c}) = \frac{P(\Omega_{T_c}|\mathcal{H}_{p1}) * P(\mathcal{H}_{p1})}{P(\Omega_{T_c}|\mathcal{H}_{p1}) * P(\mathcal{H}_{p1}) + P(\Omega_{T_c}|\mathcal{H}_{p0}) * P(\mathcal{H}_{p0})}, \tag{4.4.4}$$

where $P(\Omega_{T_c}|\mathcal{H}_{p0})$ and $P(\Omega_{T_c}|\mathcal{H}_{p1})$, are the conditional probabilities that the sensing information, Ω_{T_c}, is given when the primary bandwidth is under-utilized or busy, respectively. The conditional probabilities $P(\Omega_{R_c}|\mathcal{H}_{p0})$, $P(\Omega_{R_c}|\mathcal{H}_{p1})$, $P(\Omega_{T_c}|\mathcal{H}_{p0})$ and $P(\Omega_{T_c}|\mathcal{H}_{p1})$ can be found from the collected sensing information using the method in [95]. Information of $P(\mathcal{H}_{p1})$ and $P(\mathcal{H}_{p0})$ can be acquired through successive spectrum sensing of the primary users' activity.

4.5 Optimization Problem Formulation

In this section the joint SNR-target and spreading factor optimization of the reference CU is formulated. The goal is to find the optimal SNR-target and consequently the optimum variable spreading factor with respect to the number of active primary and cognitive users and subsequently use it to maximize the average spectral efficiency. This problem can be formulated as:

$$\max_{\sigma_{c,f_c}(.),\,\sigma_{c,f_p}(.)} \quad \frac{R}{B} = P_I \frac{N_{chip}}{B} \sum_{k=1}^{k_{max}} \frac{1}{N_{c,f_p}\left(k; BER_{c,f_p}^{t}\right)} h(k)$$

$$+P_B \frac{N_{chip}}{B} \sum_{n=2}^{n_{max}} \frac{1}{N_{c,f_c}(n; BER_{c,f_c}^{t})} r(n),$$

subject to

$$\sum_{k=1}^{k_{limit}} \int_{\gamma_{c,f_p}} S_{c,f_p}\left(\gamma_{c,f_p}, k\right) h(k) f_{\Gamma}\left(\gamma_{c,f_p}\right) d\gamma_{c,f_p} \leq \bar{S}_{\,c,f_p},$$

and

$$\sum_{n=2}^{n_{max}} \int_{\gamma_{c,f_c}} S_{c,f_c}(\gamma_{c,f_c}, n) r(n) f_{\Gamma}(\gamma_{c,f_c}) d\gamma_{c,f_c} \leq \bar{S}_{\,c,f_c}\,,$$

(4.5.1)

where $R/_B$ denotes the total average spectral efficiency of the reference CU (average spectral efficiency of a fraction of time that it utilizes the primary spectrum plus the average spectral efficiency when it exploits the cognitive network bandwidth), N_{chip} is the number of chips per unit time and $h(k)$ and $r(n)$ are the distribution of k and n, respectively. The Lagrangian of this problem can be created

$$L\left(\sigma_{c,f_c}(.), \sigma_{c,f_p}(.), \theta_1, \theta_2\right) =$$

$$P_I \frac{N_{chip}}{B} \sum_{k=1}^{k_{max}} \frac{1}{N_{c,f_p}(k; BER_{c,f_p}^t)} h(k) + P_B \frac{N_{chip}}{B} \sum_{n=2}^{n_{max}} \frac{1}{N_{c,f_c}(n; BER_{c,f_c}^t)} r(n)$$
$$+ \theta_1 \left(\sum_{k=1}^{k_{max}} \int_{\gamma_{c,f_p}} \frac{\sigma_{c,f_p}\left(k; BER_{c,f_p}^t\right)}{\gamma_{c,f_p}} h(k) f_\Gamma\left(\gamma_{c,f_p}\right) d\gamma_{c,f_p} - 1 \right)$$
$$+ \theta_2 \left(\sum_{n=2}^{n_{max}} \int_{\gamma_{c,f_c}} \frac{\sigma_{c,f_c}\left(BER_{c,f_c}^t\right)}{\gamma_{c,f_c}} r(n) f_\Gamma\left(\gamma_{c,f_c}\right) d\gamma_{c,f_c} - 1 \right), \tag{4.5.2}$$

to obtain the optimal value of $\sigma_{c,f_p}\left(k; BER_{c,f_p}^t\right)$ and $\sigma_{c,f_c}\left(n; BER_{c,f_c}^t\right)$, where θ_1 and θ_2 represent the Lagrangian multipliers.

4.6 Adaptive SNR-target and Spreading Factor

The SNR at the output of the cognitive receiver matched-filter detector when the primary frequency band is being used by the reference CU, can be approximated as:

$$SNR_{c,f_p} = \left\{ \frac{q_{c,f_p}(L_p, \delta) - 1}{2N_{c,f_p}\left(k; BER_{c,f_p}^t\right)} + \frac{k q_{c,f_p}(L_p, \delta)}{3N_{c,f_p}\left(k; BER_{c,f_p}^t\right)} + \frac{N_0}{2E_b \Xi_{c,f_p}} \right\}^{-1}, \tag{4.6.1}$$

where Ξ_{c,f_p} is the path strength of g_{c,f_p}, E_b represents the bit energy and the parameter $q_{c,f_p}(L_p, \delta)$ is a function of the total number of paths received from the reference user, denoted by L_p, and the rate of exponential decay of MIP, is denoted by δ.

The SNR is given by (4.6.2) when the cognitive network spectrum is utilized by the reference CU.

$$SNR_{c,f_c} = \left\{ \frac{q_{c,f_c}(L_p, \delta) - 1}{2N_{c,f_c}(n; BER^t_{c,f_c})} + \frac{(n-1)q_{c,f_c}(L_p, \delta)}{3N_{c,f_c}(n; BER^t_{c,f_c})} + \frac{N_0}{2E_b \Xi_{c,f_c}} \right\}^{-1}, \tag{4.6.2}$$

where Ξ_{c,f_c} is the path strength of g_{c,f_c} and the parameter $q_{c,f_c}(L_p, \delta)$ is a function of the total number of paths received from the reference user.

With proper scaling of the average transmit power of the reference CU, it can be assumed that $\Xi_{c,f_p} = \Xi_{c,f_c} = 1$. Using the same method explained in Chapter 3, the spreading factor for a matched-filter-based receiver when the primary frequency band is used by reference CU for transmission is derived as:

$$N_{c,f_p}\left(k; BER^t_{c,f_p}\right) = \frac{-\ln\left(2BER^t_{c,f_p}\right)\sigma_{c,f_p}\left(k; BER^t_{c,f_p}\right)\Phi_{c,f_p}}{6\ln\left(2BER^t_{c,f_p}\right) + 3\sigma_{c,f_p}\left(k; BER^t_{c,f_p}\right)}, \tag{4.6.3}$$

where

$$\Phi_{c,f_p} = 3\left(q_{c,f_p}(L_p, \delta) - 1\right) + 2\left[k q_{c,f_p}(L_p, \delta)\right]. \tag{4.6.4}$$

Moreover, for a fraction of time that reference CU exploits the cognitive spectrum for data transmitting, the spreading factor is set by

$$N_{c,f_c}(n; BER^t_{c,f_c}) = \frac{-\ln(2BER^t_{c,f_c})\,\sigma_{c,f_c}(n; BER^t_{c,f_c})\,\Phi_{c,f_c}}{6\ln(2BER^t_{c,f_c}) + 3\sigma_{c,f_c}(n; BER^t_{c,f_c})}, \tag{4.6.5}$$

where

$$\Phi_{c,f_c} = 3\left(q_{c,f_c}(L_p, \delta) - 1\right) + 2\left[(n-1)q_{c,f_c}(L_p, \delta)\right]. \tag{4.6.6}$$

By setting the result of derivation of $L\left(\sigma_{c,f_c}(.), \sigma_{c,f_p}(.), \theta_1, \theta_2\right)$ with respect to $\sigma_{c,f_p}\left(k; BER_{c,f_p}^t\right)$ equal to zero, the optimal outer loop SNR-target for the matched filter detector when the primary frequency band is used by the reference CU can be derived as

$$\sigma_{c,f_p}\left(k; BER_{c,f_p}^t\right) = \sqrt{\frac{-P_I 6 N_{chip}}{\theta_1 E\left[1/\gamma_{c,f_p}\right] \Phi_{c,f_p} B}}. \tag{4.6.7}$$

Also by solving $\partial L/\partial \sigma_{c,f_c}(.) = 0$, the optimum SNR-target for a fraction of time that the reference CU is utilizing the cognitive spectrum can be derived as

$$\sigma_{c,f_c}\left(n; BER_{c,f_c}^t\right) = \sqrt{\frac{-P_B 6 N_{chip}}{\theta_2 E\left[1/\gamma_{c,f_c}\right] \Phi_{c,f_c} B}}, \tag{4.6.8}$$

where θ_1 and θ_2 depend on the distribution of k and n, $h(k)$ and $r(n)$, respectively. It is assumed that the numbers of active primary and cognitive users in the cell are modelled as a Poisson random variable, with the same pdfs as used in Chapter 3.

The optimal outer loop SNR-target of (4.6.7) and (4.6.8) can be applied in (4.6.3) and (4.6.5), respectively, to calculate the optimal $N_{c,f_p}\left(k; BER_{c,f_p}^t\right)$ and $N_{c,f_c}\left(n; BER_{c,f_c}^t\right)$, respectively. Consequently, by substituting the optimal value of variable spreading factor into objective function in (4.5.1), the maximum total achievable average spectral efficiency of the reference CU is obtained as

$$\begin{aligned}\frac{R}{B} = &-\frac{3P_I N_{chip}}{B} e^{-\lambda_p/\mu_p}\left(\frac{\Psi_{c,f_p}}{\ln\left(2BER_{c,f_p}^t\right)} + 2{\zeta_{c,f_p}}^2 E\left[1/\gamma_{c,f_p}\right] e^{-\lambda_p/\mu_p}\right) \\ &-\frac{3P_B N_{chip}}{B} e^{-\lambda_c/\mu_c}\left(\frac{\Psi_{c,f_c}}{\ln\left(2BER_{c,f_c}^t\right)} + 2{\zeta_{c,f_c}}^2 E\left[1/\gamma_{c,f_c}\right] e^{-\lambda_c/\mu_c}\right),\end{aligned} \tag{4.6.9}$$

where

$$\zeta_{c,f_p} = \sum_{k=1}^{k_{max}} \frac{1}{\sqrt{\Phi_{c,f_p}}} \frac{\left(\lambda_p/\mu_p\right)^k}{k!}, \tag{4.6.10}$$

$$\zeta_{c,f_c} = \sum_{n=2}^{n_{max}} \frac{1}{\sqrt{\Phi_{c,f_c}}} \frac{(\lambda_c/\mu_c)^n}{n!}. \tag{4.6.11}$$

$$\Psi_{c,f_p} = \sum_{k=1}^{k_{max}} \frac{1}{\Phi_{c,f_p}} \frac{\left(\lambda_p/\mu_p\right)^k}{k!}, \tag{4.6.12}$$

and

$$\Psi_{c,f_c} = \sum_{n=2}^{n_{max}} \frac{1}{\Phi_{c,f_c}} \frac{(\lambda_c/\mu_c)^n}{n!}. \tag{4.6.13}$$

4.7 Numerical Results

This section evaluates the performance of the system that uses the AB-OSA technique to utilize the primary spectrum and employs the proposed joint-optimization scheme. The numerical results are displayed under flat fading ($L_p = 1$) and multipath fading ($L_p \geq 1$) conditions. The performance of the proposed joint-optimization method compared to the variable spreading factor system, which does not make use of the optimum SNR target in the outer loop. The latter is referred to as non-optimized system and in this system the SNR-target when the primary spectrum is idle and busy is kept constant: $\sigma_{c,f_p} = 1/E\left[1/\gamma_{c,f_p}\right]$ and $\sigma_{c,f_c} = 1/E\left[1/\gamma_{c,f_c}\right]$, respectively. To achieve a commensurate assessment of both systems, it is assumed that both the optimized and the non-optimized systems have the same average transmit power and instantaneous SNR for both primary and cognitive users. Although different sensing information at the reference CU transmitter and receiver may be collected, but without loss of generality and by assuming a perfect channel sensing, it is considered that $P_B = 1 - P_I$. Throughout the evaluation, the maximum number of primary and cognitive users is set to $k_{max} = 30$ and $n_{max} = 70$ respectively, and also $k_{limit} = 15$. Also it is assumed that channel bandwidth is $B = 5$ MHz, chip rate is $N_{chip} = 3.84$ Mcps, $\bar{S} = 0.25$ Watt and $N_0 = -174$ dBm/Hz.

Fig 4.2 illustrates the attainable gain in the reference CU throughput by using the CR technology. Two different scenarios are considered. In the first scenario, it is assumed that the primary spectrum is always busy, $P_I = 0$, and the reference CU can only utilize the cognitive bandwidth, this scenario is called a non-shared-spectrum case. In the second scenario, the primary frequency band is always under-utilized, $P_I = 1$; therefore the reference CU only uses the primary bandwidth for transmitting data. The latter is referred to as a shared-spectrum scheme. The figure shows that significant gain can be achieved in the average spectral efficiency of the reference CU by employing the CR technology. For instance, at $E\left[\gamma_{c,f_c}\right] = E\left[\gamma_{c,f_p}\right] =$ 35 dB, the average spectral efficiency decreases by nearly 90% by changing $P_I = 1$ to $P_I = 0$. The reasonable explanation for this loss is that for a case that $P_I = 0$, the reference CU is only allowed to utilize the cognitive spectrum, and the cognitive network is saturated so the resulting MAI causes a severe degradation is the reference CU performance. Whereas, it would experience a much better performance during a time that it exploits the primary spectrum as lower number of users communicating in the primary cell and therefore lower MAI is generated. In addition, it is observed that the joint-optimization methods can also enhance the efficient utilization of the bandwidth. A significant improvement in the reference CU's average spectral efficiency is achieved particularly in the lower average SNRs region.

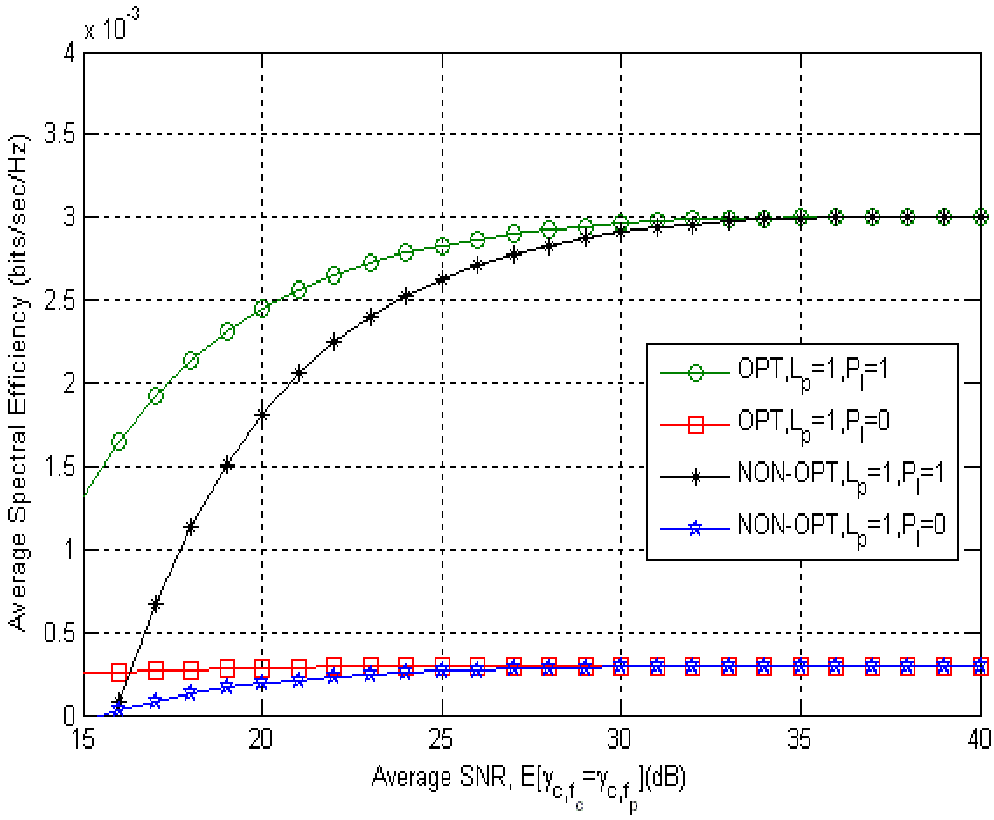

Figure 4.2: Optimized and non-optimized average spectral efficiency for shared and non-shared spectrum systems, when $\lambda_p = 0.4$, $\mu_p = 0.0085$, $\lambda_c = 0.8$, $\mu_c = 0.01$, $m = 2$, $\delta = 0, BER^t_{c,f_p} = 10^{-4}$, $BER^t_{c,f_c} = 10^{-4}$.

In Fig. 4.3 the optimal and the non-optimal average spectral efficiency values are demonstrated for various numbers of paths. It is evident that the significant enhancement in the spectral efficiency occurs by using the proposed joint-optimization scheme mainly in the lower average SNR region. Furthermore, a higher number of paths require a larger spreading factor and this subsequently results in a smaller average spectral efficiency. The BER-target of both primary and cognitive networks is set to 10^{-4} to maintain the communication quality for typical service.

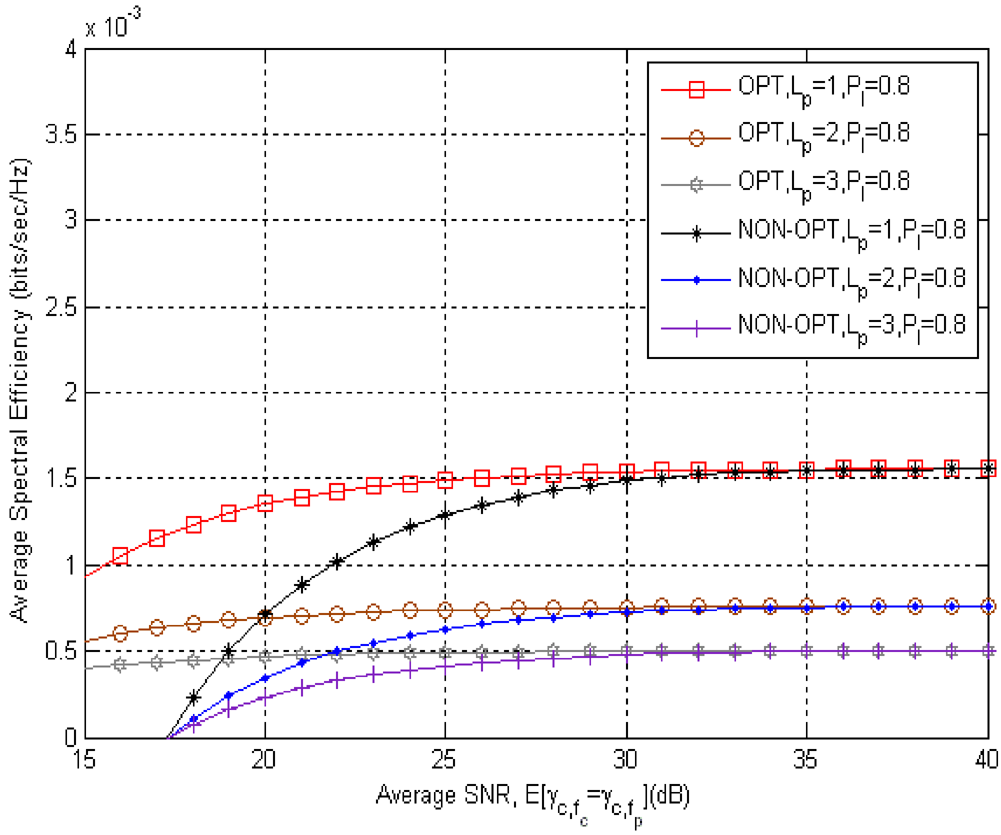

Figure 4.3: Average spectral efficiency of the reference CU for different number of paths, when $\lambda_p = 0.30$, $\mu_p = 0.009$, $\lambda_c = 0.44$, $\mu_c = 0.0064$, $m = 2$, $BER^t_{c,f_p} = BER^t_{c,f_c} = 10^{-4}$, $\delta = 0$.

Fig. 4.4 illustrates the achievable average spectral efficiency of the reference CU for the optimized and the non-optimized scenario for different values of the probability of the primary channel is being available to the reference CU for transmitting data (primary spectrum being idle), P_I. It is observable that the average spectral efficiency is significantly enhanced by increasing the probability that the licensed primary signal is accessible to the reference CU. Additionally, it is observed that the proposed optimization scheme always outperforms the non-optimal transmissions.

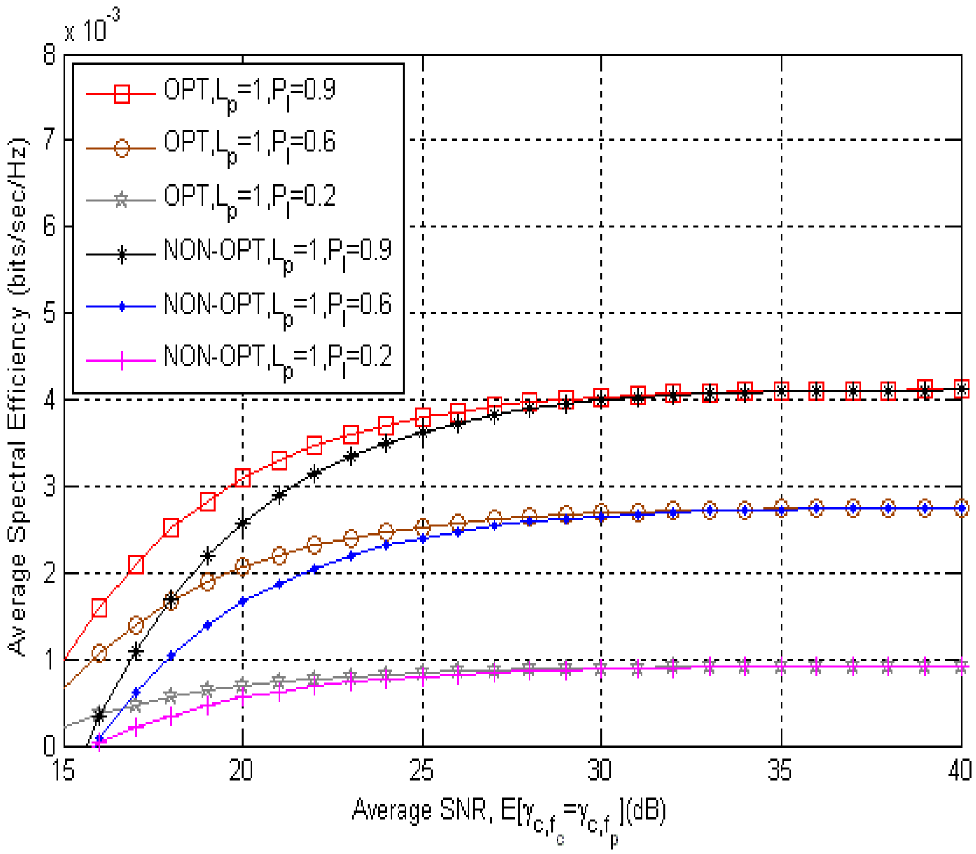

Figure 4.4: Average spectral efficiency of the reference CU for different value of P_I, when $\lambda_p = 0.36$, $\mu_p = 0.009$, $\lambda_c = 0.59$, $\mu_c = 0.003$, $m = 2$, $BER^t_{c,f_p} = 10^{-4}$, $BER^t_{c,f_c} = 10^{-4}$, $\delta = 0$.

In Fig. 4.5, the average spectral efficiency is plotted for a range of P_I. As the probability of the primary network being idle rises, so does the achievable total average spectral efficiency of the reference CU. The figure shows the average spectral efficiency of the reference CU for different values of average SNR for both the optimized and the non-optimized scenarios. Apart from the improvement achieved by the joint-optimization scheme, it is observed that increasing the probability that the number of active primary users is less than threshold, primary spectrum being idle, causes a considerable gain in the value of average spectral efficiency.

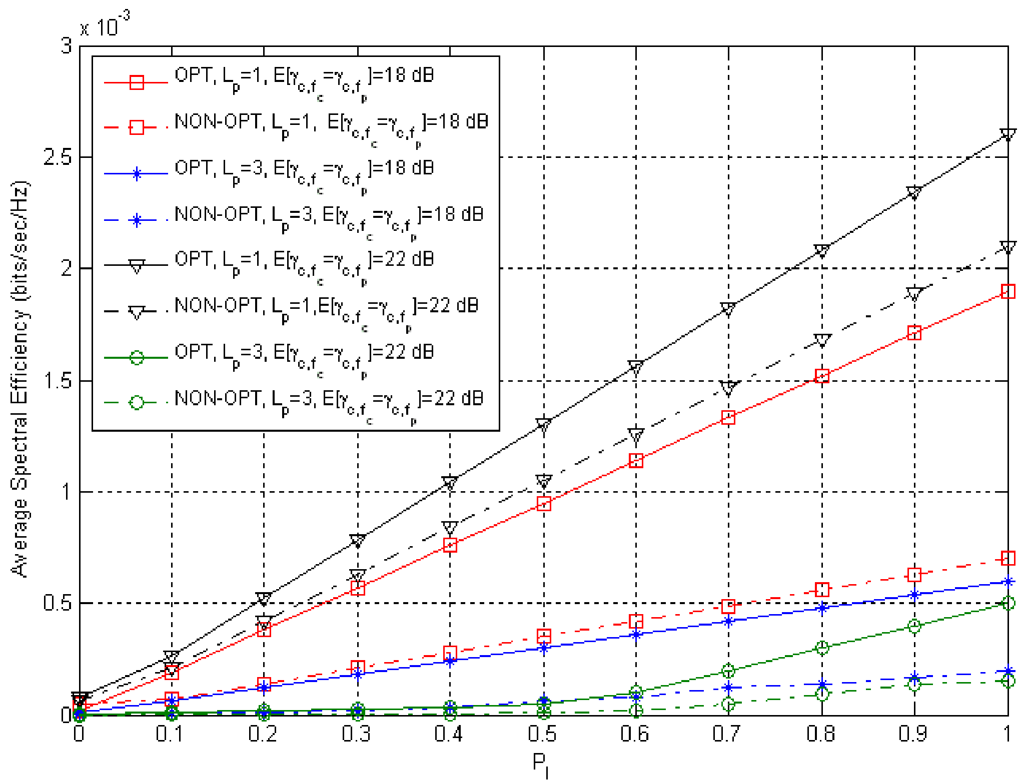

Figure 4.5: Average spectral efficiency of the optimized and the non-optimized systems for various numbers of paths, *vs.* conditional probability that the primary signal is idle, when $\lambda_p = 0.40$, $\mu_p = 0.009$, $\lambda_c = 0.8$, $\mu_c = 0.0064$, $m = 2$, $BER^t_{c,f_p} = BER^t_{c,f_c} = 10^{-4}$, $\delta = 0$.

Finally, Fig. 4.6 demonstrates the average spectral efficiency for various BER-targets, BER^t_{c,f_p} and BER^t_{c,f_c}, and different values of P_I, when the number of paths set to 2, for both the optimized and the non-optimized scenarios. It is observed that the average spectral efficiency of the optimized method converges to that of the non-optimized method in higher region of SNR. As a result, the proposed method is effective mostly in the lower SNR region. In addition to the gains achieved by the proposed optimized scheme over the non-optimized one, a more relaxed BER-target yields higher average spectral efficiency.

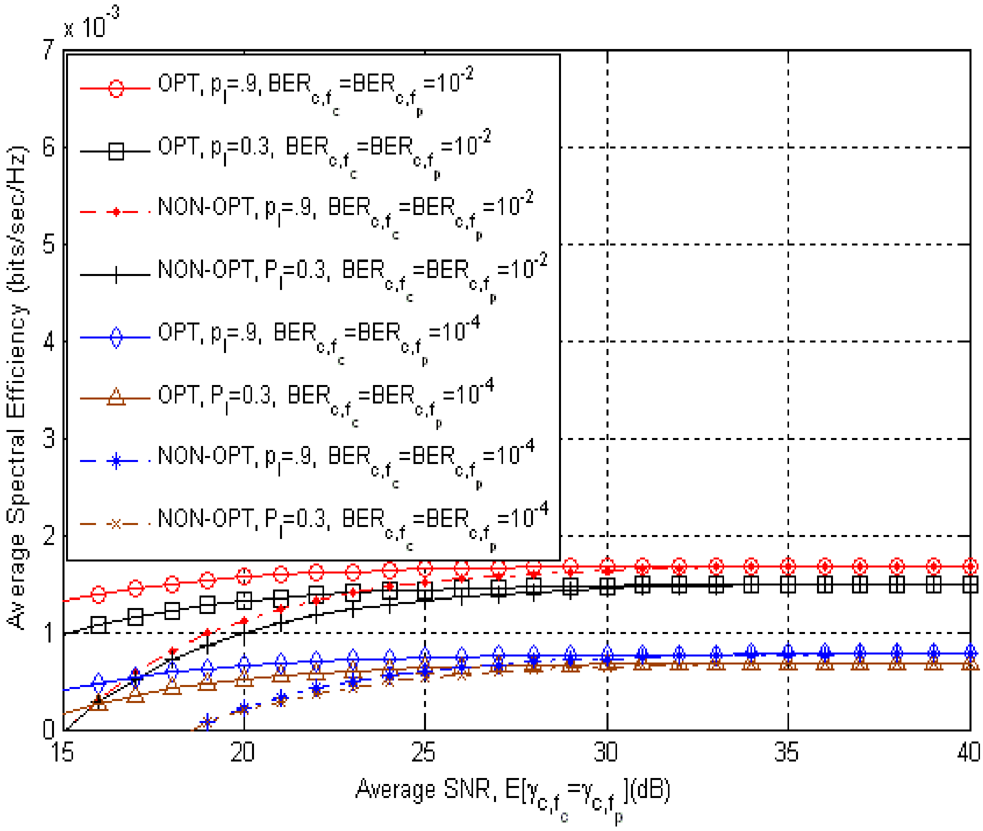

Figure 4.6: Optimized and non-optimized average spectral efficiency for different BER and P_I values, when $L_p = 2,\ \lambda_p = 0.3\ ,\ \mu_p = 0.009,\ \lambda_c = 0.30\ ,\ \mu_c = 0.0064,\ m = 2,$ $\delta = 0$.

4.8 Summary

This chapter analyzed the joint-optimization scheme proposed in Chapter 3, for a scenario that the CUs are using AB-OSA technique for exploiting the primary frequency band. Particularly a multi-user cognitive service that exploits the aforementioned joint-optimization technique is considered and the proposed scheme performance is evaluated when a matched-filter detector is used in the receiver of the reference CU. Such a CR service utilizes the primary spectrum when it is idle, under-utilized, and the reference CU collects the information about the availability of the primary frequency band through spectrum sensing. Therefore, the CUs utilize the primary spectrum when the number of active primary users is below the pre-defined threshold. During the fraction of time that the reference CU is not permitted to access the primary frequency band, it would use the cognitive network spectrum for transmitting data. The spectral efficiency of the proposed scheme is compared to a system that does not use optimal SNR-target. A considerable gain was demonstrated by using the proposed optimization technique mainly in the lower region of SNR. Also, it was shown in the numerical section that reference CU performance is significantly improved by using the shared-spectrum scheme, comparing to non-shared-spectrum case. Obtained results also show that as a more relaxed BER-target is used, more average spectral efficiency is attained.

Chapter 5

5. Probabilistic Optimization of Share-Spectrum CR Networks

5.1 Contributions

This chapter will develop:

- A novel access strategy (AB-IL-OSA) for CDMA/CDMA shared-spectrum CR networks that achieved a trade-off between the primary network's QoS requirements and the cognitive network's throughput.

The following derivations were made for total power adaptation policy:

- A closed-form solution for the average spectral efficiency of the reference CU under the frequency-selective Rayleigh multipath fading channel conditions.
- A closed-from solution for the reference CU's optimal SNR-target subject to both the average and the peak received-interference constraints.

5.2 Introduction

Chapter 3 and 4 of this thesis evaluate the performance of the CUs when they utilize the primary spectrum using IL-OSA and AB-OSA, respectively. Although, using each of these access strategies, as numerically illustrated in previous chapters, can improve the CUs' achievable throughput, but the optimal performance cannot be achieved due to a number of limitations and challenges that results in missing the spectrum opportunities. For instance, in AB-OSA strategy, the CUs transmission is stopped when the primary spectrum is busy, therefore the CUs are missing some sharing opportunities which are due to the interference tolerability of the primary network. Similarly, the CUs' throughput is reduced in IL-OSA technique, as a result of implied interference constraint that restricts transmission power of the CUs even during the idle periods. Therefore, it is significantly important to find new access strategies to address those aforementioned issues.

Some of the recent works in this domain was reviewed in Chapter 2. However, based on the used radio access technology, some other issues should also be addressed when each of those aforementioned access strategies is used. For example, the QoS requirements of the primary users would not be satisfied at each instant when DS-CDMA air interface technology is used in AB-OSA systems. In the CDMA/CDMA shared spectrum CR systems, by using AB-OSA strategy, the CUs' operation in the primary bandwidth during the time that the primary spectrum is idle, may violate the QoS conditions of the primary users and degrade their performance. This is due to the fact that in CDMA/CDMA, CR system, even for a fraction of time that the primary bandwidth is assumed idle by the reference CU, there are still a number of active primary users in the primary cell, which their QoS requirements should be satisfied.

This chapter proposes a novel access strategy to address the aforementioned limitation issue of AB-OSA technique. This novel access strategy is referred to as an Access Bounded and Interference Limited OSA (AB-IL-OSA). In AB-IL-OSA systems, the duration of the time that the CUs is permitted to utilize the licensed spectrum is limited based on the activity of the primary network. The CUs can transmit data over the primary frequency band when the number of active users (active primary users plus other CUs exploiting the primary frequency band,) is below a pre-defined limit. Simultaneously, the MAI caused by the performance of the CUs in the primary network frequency band should also be limited, so the operation of the CUs is restricted based on the amount of interference caused by the CU's activity on the primary receiver. Although using the AB-IL-OSA scheme may downgrade the performance of the CUs but attention should be always paid to this point that the primary frequency band is allocated to the primary users and their QoS provisioning should not be degraded by the CUs' operation. Therefore, using the proposed scheme guarantees the QoS requirements of the primary users at each instant by stopping the CUs' operation during the busy periods and by checking that the CUs' interference remains below the tolerable level when the primary network is under-utilized. In this chapter, using the proposed joint optimization scheme in Chapter 3, the average spectral efficiency of the CUs is investigated under the joint peak and average received-interference threshold constraints, where the spectrum sensing technique is used to exploit OSA flexibility. The performance of the reference CU is investigated in a multi-user CR system where CDMA technology is used by the primary and cognitive users for transmitting data over the shared frequency spectrum under the frequency-selective Rayleigh multipath fading channel conditions.

This chapter uses same assumption and parameters expressed in the Chapter 3 and 4, therefore, it does not include procedures and approaches of deriving the previously mentioned parameters and algorithm and only the final outcomes are mentioned in this chapter.

The rest of this chapter is structured as follows: Section 5.3 describes the system model and operation assumptions. Section 5.4 analyzes the CUs' average spectral efficiency when AB-IL-OSA technique is used for accessing the primary spectrum. Section 5.5 discusses the numerical results. Finally, section 5.6 summarizes the chapter.

5.3 System Model

A CR system with $k(t), 1 \le k(t) \le k_{max}$, active primary users and $n(t), 1 \le n(t) \le n_{max}$ active CUs that exploit the primary frequency band at time t is considered, where k_{max} and n_{max} respectively represent the maximum number of primary and cognitive user at any given time respectively. The cognitive and primary users transmit data over the reverse link of multiuser DS-CDMA cellular radio system. The signal of both primary and cognitive users is spread over a bandwidth B by spreading factor $N(k(t), n(t); P_b)$, where P_b indicates the target bit error rate for both primary and cognitive users. Zero-mean AWGN, $n(t)$, with a two-sided power spectral density of $N_0/2$, is added to the BPSK-modulated signal. An L_p-path time-varying fading channel with stationary channel gains $g_{(p_i p)_j}(t)$, $g_{(p_i c)_j}(t)$, $g_{(c_i c)_j}(t)$, and $g_{(c_i p)_j}(t)$, between the primary transmitter-i and the primary receiver, the primary transmitter-i and the cognitive receiver, and between the cognitive transmitter-i and the cognitive receiver, and between the cognitive transmitter-i and the primary receiver, are assumed over path-j at time t, respectively, where $j = 1, .., L_p$. We assume that a centralized power control mechanism is employed in both primary and cognitive networks. Here, the average spectral efficiency of the reference CU in the presence of k primary users and n cognitive users is studied. The stationary channel gains, over path-j at time t, between the reference CU's transmitter and the primary receiver, and between the reference CU's transmitter and the cognitive receiver, respectively, are denoted by $g_{(cp)_j}(t)$, $g_{(c)_j}(t)$.

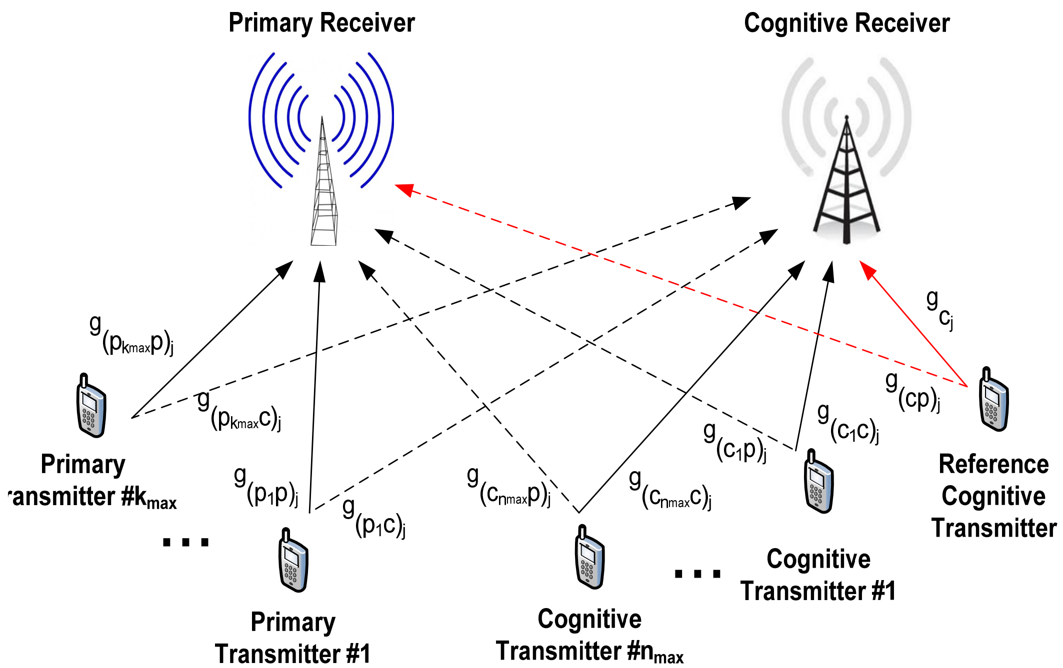

Figure 5.1: System model.

Fig. 5.1 depicts the schematic diagram of the opportunistic spectrum sharing scenario. For simplicity, only single paths are drawn. The instantaneous received SNR of the reference CU at the output of the MRC combiner at the cognitive receiver can be written as

$$\gamma_c(t) = \frac{\bar{S}\ \sum_{j=1}^{L_p} \left|g_{(c)_j}(t)\ \right|^2}{N_0 B}, \tag{5.3.1}$$

where $\bar{S}$ denotes the average transmit power of reference CU. Also, $\left|g_{cp}(t)\right|^2 = \sum_{j=1}^{L_p} \left|g_{cp_j}(t)\right|^2$ is defined as the total channel power gain between the cognitive transmitter and the output of MRC combiner at the primary receiver.

The notion of time t is omitted in the rest of this chapter because $\gamma_c(t)$ and $g_{cp}(t)$ are assumed to be stationary. In the outer loop, the SNR-target, $\sigma(k, n; P_b)$, is set based on the number of active primary and cognitive users and P_b. In order to attain the SNR-target the transmit power of the reference CU, $S(\gamma_c, k, n)$, is adapted to the received SNR, γ_c, and the number of users utilizing the primary frequency band, through the channel inversion policy

$$\frac{S(\gamma_c, k, n)}{\bar{S}} = \frac{\sigma(k, n; P_b)}{\gamma_c}. \tag{5.3.2}$$

5.4 Adaptive Transmission

The reference CU operation in the primary frequency spectrum should not degrade the performance of the primary users or violate their QoS requirements. Consequently, the reference CU is only allowed to exploit the primary frequency band when it is under-utilized which is defined here as the period of time that the number of active users (active primary users plus active CUs) in the primary network is below the pre-set limit, l_{limit}. However, even during this fraction of time, as the primary CDMA users are sharing a single frequency carrier, there are still some active primary users, which the transmission pertaining to the reference CU should not harm their signal quality at the receiver of the primary network. Accordingly, constraints are imposed on both average and peak received-interferences power inflicted on the primary receiver by the activity of the reference CU.

Suppose k_{limit} and n_{limit} indicate the maximum number of active primary and cognitive users respectively during the time that primary network is under-utilized. This chapter uses the same spectrum sensing algorithm that expressed in Chapter 4 with only this difference that the reference CU is allowed to utilize the primary spectrum if total number of active users $(k_{limit} + n_{limit})$ in the primary cell is lower that pre-set threshold, l_{limit}. The average received-interference and the peak received-interference constraints are respectively defined as

$$\sum_{n=1}^{n_{limit}} \sum_{k=1}^{k_{limit}} \int_{\gamma_c, g_{cp}} g_{cp} S_c(\gamma_c, k, n)\, r(n) h(k) f_G(g_{cp}) f_\Gamma(\gamma_c) dg_{cp}\, d\gamma_c \leq Q_{avg},$$

and

$$g_{cp} S_c(\gamma_c, k, n) \leq Q_{peak}\,, \tag{5.4.1}$$

where Q_{avg} and Q_{peak} denote the average and peak received-interference values respectively.

The goal is to find the optimal value of SNR-target by using outer loop power control, and then achieve it by choosing the most suitable spreading factor for transmission. This will thus maximize the average spectral efficiency of the reference CU. Hence, the maximum average spectral efficiency of the reference CU, i.e. data rate, R, per unit bandwidth, B, would be the solution to the following problem:

$$\frac{R}{B} = \max_{\sigma(.,.)} \quad \frac{P_I N_{chip}}{B} E_{k,n}\left[\frac{1}{N(k, n; P_b)}\right],$$

subject to

$$\sum_{n=1}^{n_{limit}}\sum_{k=1}^{k_{limit}}\int_{\gamma_c, g_{cp}} g_{cp}\frac{\sigma(k,n;P_b)}{\gamma_c}r(n)h(k)f_G(g_{cp})f_\Gamma(\gamma_c)dg_{cp}\,d\gamma_c \le \frac{Q_{avg}}{\bar{S}},$$

and

$$g_{cp}\frac{\sigma(k,n;P_b)}{\gamma_c} \le Q_{peak},$$

(5.4.2)

where N_{chip} is the number of chips per unit time, P_I is the conditional probability that the primary network spectrum being idle and $N(k,n;P_b)$ is the spreading factor for matched-filter-based receiver as derived in Chapter 3. To find the maximum average spectral efficiency of the reference CU, the Lagrangian function is created and by adopting the similar approach used in Chapter 3, the optimal SNR-target can be found as

$$\sigma(k,n;P_b) = \begin{cases} \sqrt{\dfrac{-6P_I N_{chip}}{B\theta\Phi(k,n)E[v]}} & v \ge \dfrac{Q_{peak}}{\bar{S}}, \\ \dfrac{Q_{peak}}{v\bar{S}} & v \le \dfrac{Q_{peak}}{\bar{S}}, \end{cases}$$

(5.4.3)

where θ is the Lagrangian multiplier, $\Phi(k,n) = \left[3\left(q(L_p,\delta) - 1\right) + 2(k+n)q(L_p,\delta)\right]$ and $v = \left|g_{cp}\right|^2/\gamma_c$. Recalling that the distribution of the ratio between two Gamma distributed random variables with parameters α_1 and α_2 is a Beta prime distribution with parameters α_1 and α_2, the distribution of v can be written as:

$$f_V(v) = \frac{1}{(v+1)^2}.$$

(5.4.4)

Suppose that the number of active primary and cognitive users in the cell is Poisson random variables and by using the same pdfs used in Chapter 3, a closed-form expression for the maximum average spectral efficiency can be derived by averaging of

R/B over all values of v, (the optimal value of Lagrangian multiplier and optimum spreading factor are found by adopting a similar approach used in Chapter 3.)

$$\left(\frac{R}{B}\right)_{max} = \frac{-3P_I N_{chip}}{B} e^{-(\lambda_p/\mu_p+\lambda_c/\mu_c)} \left[\frac{2\zeta_{limit}E[v]\zeta\bar{S}}{\chi Q_{\text{avg}}} e^{-(\lambda_p/\mu_p+\lambda_c/\mu_c)} + \frac{\Psi}{ln\, 2P_b} + \frac{2\bar{S}\Psi}{Q_{peak}}\left(ln(\chi) + \left(\frac{1}{\chi}\right) - 1\right)\right], \tag{5.4.5}$$

where

$$\zeta = \sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} \frac{1}{\sqrt{\Phi(k,n)}} \frac{\left(\lambda_p/\mu_p\right)^k}{k!} \frac{(\lambda_c/\mu_c)^n}{n!}, \tag{5.4.6}$$

$$\zeta_{limit} = \sum_{n=1}^{n_{limit}} \sum_{k=1}^{k_{limit}} \frac{1}{\sqrt{\Phi(k,n)}} \frac{\left(\lambda_p/\mu_p\right)^k}{k!} \frac{(\lambda_c/\mu_c)^n}{n!}, \tag{5.4.7}$$

$$\Psi = \sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} \frac{1}{\Phi(k,n)} \frac{\left(\lambda_p/\mu_p\right)^k}{k!} \frac{(\lambda_c/\mu_c)^n}{n!}, \tag{5.4.8}$$

and

$$\chi = \left(\frac{Q_{peak}}{\bar{S}} + 1\right). \tag{5.4.9}$$

5.5 Performance Evaluation and Numerical Results

In this section, performance of the proposed joint optimization scheme is numerically assessed and compared to the system that does not make use of the optimum SNR target in the outer loop which is referred to as a non-optimized system. Hence it is assumed that in the non-optimized system the SNR-target is kept constant through the expression $\sigma = \bar{S}/Q_{\text{avg}}E\left[\left|g_{cp}\right|^2\right]E[1/\gamma_c]$. Furthermore, the system throughput under AB-IL-OSA strategy is compared to the system that uses AB-OSA technique for utilizing the primary frequency bandwidth, to evaluate the cost of reducing the probability of violating the primary network QoS requirements. Throughout the evaluation, the maximum number of primary and cognitive users is set to $k_{max} = 50$ and $n_{max} = 15$ respectively and k_{limit} =25 and n_{limit}=5. Also it is assumed that channel bandwidth is $B = 5$ MHz, chip rate is $N_{chip} = 3.84$ Mcps, $\bar{S} =$ 0.25 Watt, Q_{avg}=$10N_0B$ and $N_0 = -174$ dBm/Hz.

First, performance of the proposed optimization scheme when it utilizes the primary spectrum using the AB-IL-OSA strategy is compared to the non-optimized system for various scenarios such as, different number of paths, different value of ρ and different value of probability of the primary spectrum being idle. Then, its performance is plotted against the system that exploits AB-OSA strategy (proposed in Chapter 4) for accessing the primary network's spectrum.

Fig. 5.2 demonstrates the achievable spectral efficiency of the reference CU using the proposed joint-optimization scheme and the non-optimized method, for different number of paths. From Fig. 5.2, it is evident that the joint-optimization method provides substantial enhancement, mainly in the higher SNR region. Also increasing the number of paths results in lower average spectral efficiency.

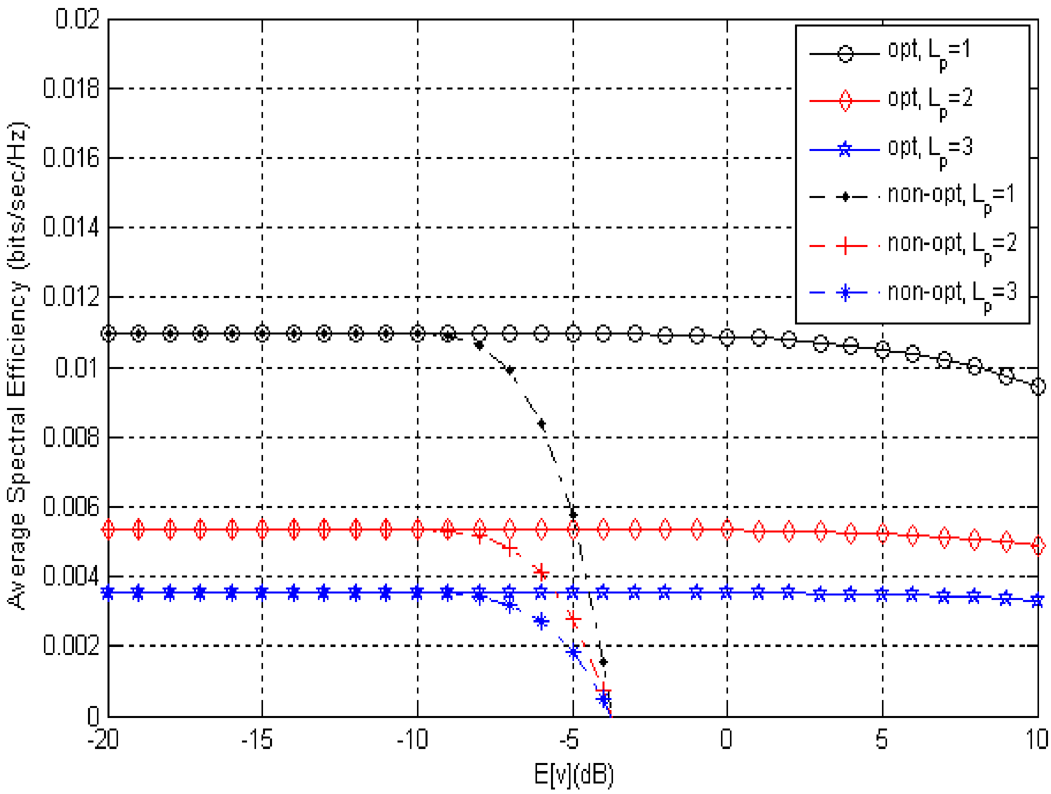

Figure 5.2: Optimized and non-optimized average spectral efficiency the reference CU for the different number of paths, when $\rho = 2$, $P_I = 0.7, P_b = 10^{-4}$, $\lambda_p = 0.2$, $\mu_p = 0.006$, $\lambda_c = 0.18$, $\mu_c = 0.08$.

In Fig. 5.3, the optimized and the non-optimized average spectral efficiency of the reference CU is plotted for various values of $\rho = Q_{\text{peak}}/Q_{\text{avg}}$. Apart from the significant gain achieved by employing the joint optimization scheme, the figure shows by increasing the valued of ρ higher average spectral efficiency can be achieved at the cost of increasing the chance of violating the primary users' QoS. For example, at $E[v] = -10$ dB, the reference CU's average spectral efficiency increases by 53% by changing the value of $\rho = 2$ to a less strict value of $\rho = 4$.

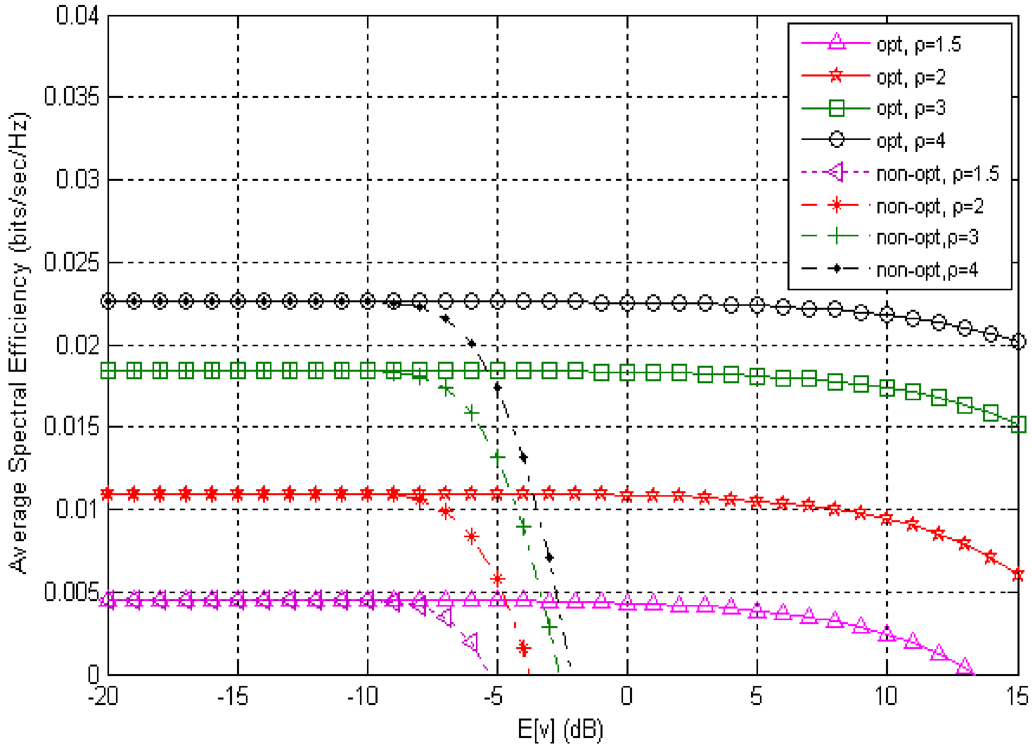

Figure 5.3: Optimized and non-optimized average spectral efficiency for different values of $\rho = Q_{\text{peak}}/Q_{\text{avg}}$, when $L_p = 1$, $P_I = 0.7, P_b = 10^{-4}$, $\lambda_p = 0.2$, $\mu_p = 0.006, \lambda_c = 0.18$, $\mu_c = 0.08$.

Fig. 5.4 illustrates the average spectral efficiency of the reference CU versus the probability of the primary network being under-utilized, P_I, for different values of ρ and different paths, for both the optimized and the non-optimized scenarios. It is observed that increasing P_I and less tight Q_{peak} constraint results in a gain in the average spectral efficiency. The reason for such a gain is that both aforementioned constraints are imposed by the primary network to guarantee the active primary users QoS. In this chapter, the reference CU's average spectral efficiency is calculated only for a fraction of time that it utilizes the primary spectrum, whereas, in Chapter 4, the total average spectral efficiency of the reference CU is derived, (for period of time that it exploits the primary spectrum plus the fraction of time that it uses the cognitive network resources for transmission). This is a reason for small throughput gain when $P_I = 0$ in Fig. 4.5.

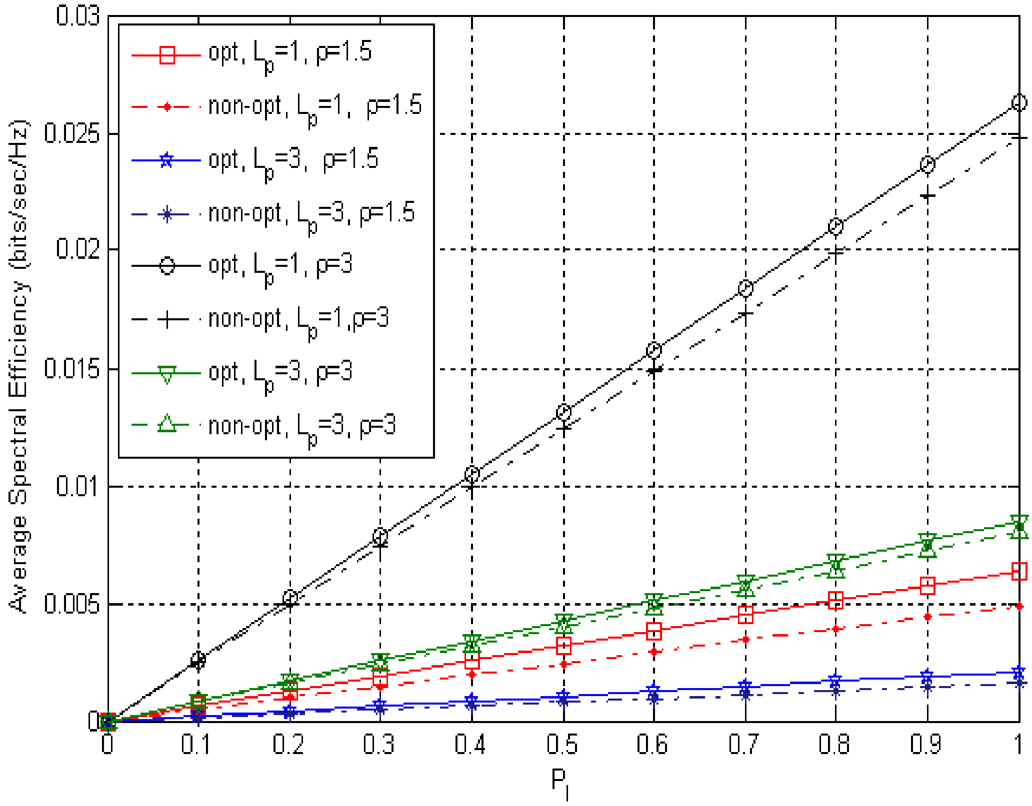

Figure 5.4: Average spectral efficiency of the optimized and the non-optimized systems for various numbers of paths, *vs.* conditional probability that the primary network is idle, when $E[v] = -7\ dB.\ \lambda_p = 0.2\ , \mu_p = 0.006,\ \lambda_c = 0.18\ , \mu_c = 0.08, P_b = 10^{-4}$.

Finally, the Fig. 5.5 shows the reference CU's average spectral efficiency under AB-OSA and AB-IL-OSA access strategies. It is observed, a better performance is achieved by using AB-OSA technique at the cost of increasing the probability of the primary network QoS violation. A good trade-off can be achieved between maintaining the primary users' QoS (which is vital in the CDMA/CDMA shared-spectrum CR networks as explained in the Introduction section of this chapter) and the CUs' throughput by using the AB-IL-OSA technique. It also, verified that under less strict interference threshold setting the throughput plots converge towards the case that AB-OSA technique is used.

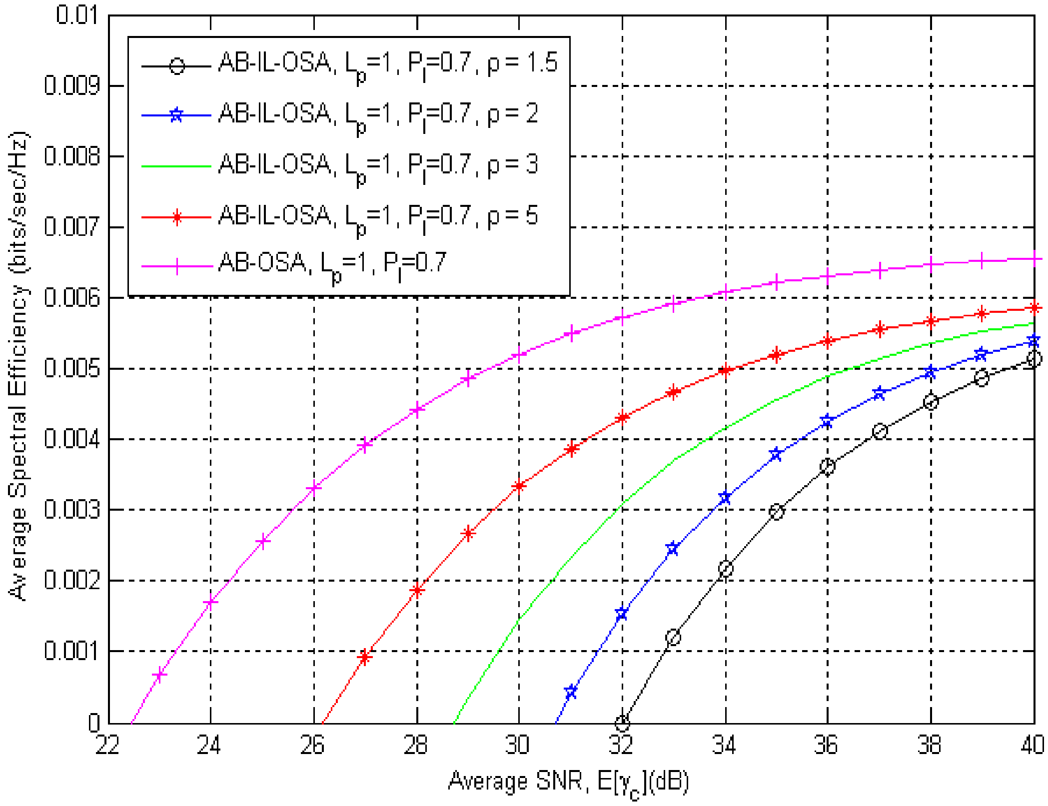

Figure 5.5: Average spectral efficiency under AB-OSA and AB-IL-OSA strategies, when $L_p = 1$, $P_I = 0.7$, $P_b = 10^{-4}$, $\lambda_p = 0.28$, $\mu_p = 0.009$, $\lambda_c = 0.18$, $\mu_c = 0.08$, $E[\gamma_{cp}] = 10dB$.

5.6 Summary

This chapter introduced a novel access strategy for the CDMA/CDMA shared-spectrum CR network that can achieve a trade-off between the primary network's QoS and cognitive network performance. It was shown that using the proposed optimization technique in Chapter 3, can enhance the reference CU's throughput when in utilizes the primary spectrum using the AB-IL-OSA. In the proposed access strategy, the reference CU access to the primary network's resources is limited based on the activity of the primary users, and also the constraints are set on both the average and the peak received-interferences, inflicted on the primary network, to guarantee the QoS requirements of the primary users. It was shown that the proposed optimization technique can improve the performance of the RCU without harming the primary users QoS, especially when the channel between the RCU's transmitter and the receiver of the primary network is weakened. Throughput performance and improvements achieved relative to the non-optimized system were also demonstrated for various number of paths and different values of ρ.

Next chapter concludes this thesis along with discussions concerning possibilities of future works.

Chapter 6

6.1 Conclusions

Radio resource management (RRM) is of paramount importance in the design of shared-spectrum CR wireless communications systems. This thesis has developed new resource allocation schemes in CR networks based on adaptive transmission power and transmission rate, two vital issues concerning RRM. With regard to sharing the spectrum between the primary and cognitive users, the system performance was investigated under different spectrum access strategies. Concerning the power allocation, the focus was on closed loop power control, which is composed of inner loop and outer loop power control. In relation to the transmission rate management, the use of variable spreading factors was employed. The goal was to develop the novel adaptive transmission techniques for the uplink of CDMA/CDMA spectrum sharing in order to enhance the average spectral efficiency of the reference CU. This technique is devised under different spectrum access strategies, namely, IL-OSA, AB-OSA and AB-IL-OSA. The aim was to accomplish the aforementioned goal in the presence of transmitter constraints, such as the CUs' power, as well as QoS requirements of both primary and cognitive networks, i.e., BER.

In Chapter 2, initially a review of various fixed and adaptive transmission rate techniques as well as classic power allocation schemes in non-shared spectrum environment were presented. There was also a discussion of different access strategies and adaptive resource allocation techniques in shared-spectrum CR networks.

In Chapter 3, a new adaptive transmission scheme was developed that involves the joint optimization of closed loop power control and transmission rate control.

IL-OSA strategy was used by the CUs for accessing the shared-spectrum; therefore, the interference caused by their operation in the primary spectrum was limited by imposing constraints on the average and the peak received-interference. Conventional matched-filter detector was considered in the receiver of both primary and cognitive networks and a closed-form solution was derived for the optimal outer loop SNR-target in terms of the number active cognitive and primary users in the primary cell. Consequently, the joint optimization of optimal SNR-target and variable spreading factor of the reference CU was analyzed. Channel inversion adaptation strategies were used in the inner loop power control, where both total and truncated policies were studied. A closed-form expression was derived for the CUs' optimal spreading factor in terms of BER-target and the optimal SNR-target. The reference CU's achievable average spectral efficiency gain was compared to a similar system that does not use the optimal SNR-target in the outer loop. In addition, an optimal trade-off between the reference CU's throughput and QoS of the primary users were obtained by dynamically setting of the peak threshold according to the number of active users in the primary network.

The proposed scheme achieved a significant enhancement in the average spectral efficiency of the reference CU mainly in the lower region of the SNRs (typically 10-25dB). The gains, however, diminished as the SNR was increased further. The impact of the INR on the maximum average spectral efficiency of the reference CU was studied. It was shown that imposing less strict BER-targets can considerably lift the spectral efficiency. The experimental results showed that higher number of paths results in smaller average spectral efficiency. Effect of both networks' higher traffic load on the average spectral efficiency of the reference CU was analyzed.

The proposed system performance was evaluated for different levels of the acceptable average received-interference threshold and it was observed that a higher average interference limit results in larger average spectral efficiency. The peak interference threshold was imposed on top of the average received-interference constraint to reduce the chance of the primary network's QoS violation. It was shown that the reference CU can achieve a higher average spectral efficiency under a less restrict peak received-interference threshold setting. The numerical results confirmed that dynamically adapting the peak interference temperature to the number of active users in the primary network can improve the performance of the proposed system. It was shown by using the aforementioned dynamic setting the reference CU's throughput increased compared to static conservative threshold-setting.

In Chapter 4, the proposed joint optimization of physical layer closed loop power control and rate control as in Chapter 3 was further analyzed for a scenario that the CUs use AB-OSA strategy for utilizing the primary frequency band. The total average spectral efficiency of the reference CU was derived subject to average transmits power and BER constraints. It was shown that allowing the reference CU to exploit the idle spectrum, by employing the CR technology, can significantly enhance its total throughput. Effect of higher probability of primary spectrum availability on the achievable average spectral efficiency of the reference CU was investigated. This was verified by numerical results and it was shown that allowing the reference CU to exploit the primary frequency band for more fraction of time can enhance its total throughput. On the other hand, during a fraction of time that the reference CU is not permitted to exploit the licensed primary spectrum, lower average spectral efficiency is attained as a result of high MAI in the cognitive network.

In Chapter 5, a novel access strategy was proposed to overcome the AB-OSA technique limitation. It was shown, AB-IL-OSA can perfectly suit the CDMA/CDMA spectrum sharing system requirements, as it can satisfy the primary network's QoS provisioning at all time, even during a fraction of time that it is assumed idle by the CUs. A closed-form expression was derived for the reference CU average spectral efficiency subject to joint average and peak received-interference constraints under the frequency-selective Rayleigh multipath fading channel conditions. The numerical results confirmed that the system can achieve a substantial gain with respect to the non-optimized systems.

6.2 Future Works

A number of potential advancement and development can be made to the proposed algorithms in this thesis. The following are a few additional ideas to be examined, with the purpose of promoting future work on these algorithms.

It would be beneficial and more practical to extend the proposed optimization algorithm into a shared-spectrum heterogeneous system. It is expected that the 3G and the 4G system to co-exist before the transition to 4G network is fully completed. Therefore, another challenge would be to examine the performance of the proposed joint optimization scheme in a OFDM/CDMA heterogeneous system (the primary network make use of Orthogonal Frequency Division Multiplexing (OFDM) and the cognitive network utilize Direct Sequence Code Division Multiple Access (DS-CDMA)). In addition, the achievable gain under different access strategies can be investigated in such a heterogeneous network.

Also, an issue of practical importance would be to extend the developed algorithms to the case of multiple-cell environment. To this end, the problem of cell membership needs to be investigated since the CUs should join the network that offers them a better service with less strict constraint. The collaborative multi-cell spectrum sharing network can be considered that allows the base-stations (BSs) to collaborate and communicate with each other to decide which network's resources can be utilized by the CUs for achieving the optimal performance.

With regard to optimization scheme developed in Chapter 3, another challenge could be to jointly control two or more of the available transmission parameters across different layers of a wireless systems in an attempt to enhance the performance. These cross-layer models try to improve system throughput while satisfying one or more of the quality of service (QoS). One scenario that could be an interesting research topic is to propose a shared-spectrum system that incorporates the joint optimization of power and rate at the physical layer and error control at the data link layer.

The assumption of perfect channel state information (CSI) available at transmitter or receiver of the CUs which was considered throughout this thesis may not hold true, therefore the impact of CSI imperfection on the performance of the proposed scheme should be investigated. One practical assumption can be, instead of considering perfect knowledge of the link between the CU's transmitter and the primary receiver is available to receiver, it can be assumed that the CUs are provided with only partial information of the link.

It is also interesting to include the probability of miss-detection and the false-alarm in the spectrum sharing system design instead of assuming a perfect spectrum sensing mechanisms, which is not practical. Therefore, impact of inaccurate spectrum sensing should be considered in the spectrum sharing problem as miss-detection incident and the collision between the primary and the cognitive network transmissions can potentially degrade the primary network performance.

Another undertaking would be examine the performance of the proposed joint optimization scheme in this thesis for other linear and/or non-linear multiuser detectors, and to observe if they exhibit similar gain.

Finally, it would be beneficial to generalize the optimization algorithm developed in this thesis for single-class systems to a multiple-class system. The reason is the various different classes that co-exist in current and future networks. For instance, a spectrum sharing system can be designed to support both real-time and non-real time services. The real-time services need low end-to-end delay and limited time variations between successive packets and can manage a higher error rates. In contrast, non-real time services such as web browsing or email require low BER but are insensitive to delays. The performance when voice users transmit at fixed-rate while the rate of data users varies could be scrutinized as a scenario appeals to practical network.

Appendix A

Proof of concavity for optimization problem (3.5.6)

In order to prove that the objective function in optimization problems (3.5.6) is concave in $\sigma(k,n)$ for all $k = 1, \dots, k_{max}$ and $= 1, \dots, n_{max}$, the second derivative of $\frac{R}{B}$ with respect to $\sigma(k,n)$ is derived.

$$\frac{d^2 \frac{R}{B}}{d^2\sigma(k,n)} = \frac{12N_{chip}}{B} \sum_{n=1}^{n_{max}} \sum_{k=1}^{k_{max}} r(n)h(k) \frac{1}{\sigma(k,n)^3 \Phi(k,n)}$$

$$k = 1, \dots, k_{max} \text{ and } n = 1, \dots, n_{max}. \tag{A.1}$$

From (3.5.7) and (3.5.11), $\sigma(k,n)$ is always a non-negative real value. Also $\Phi(k,n)$ is always a non-negative value. In addition, it is assumed that the number of active primary and cognitive users in the cell is a Poisson random variable. Also N_{chip} and B are also real and non- negative values. Therefore $\frac{d^2\frac{R}{B}}{d^2\sigma(k,n)} < 0$, for $1 \leq k \leq k_{max}$ and $1 \leq n \leq n_{max}$, and the objective function in (3.4.6) is concave. Also, the constraint in (3.5.6) is affine in $\sigma(k,n)$ for $k = 1, \dots, k_{max}$ and $n = 1, \dots, n_{max}$. Therefore conditions for applying Lagrangian method for optimization problem (3.5.6) are fulfilled.

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